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TARGET ACQUISITION AND POSITIONING STUDY (TAPS)

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Final Project Report

Prepared for:

GODDARD SPACE FLIGHT CENTER

Greenbelt, Maryland 20771

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ABSTRACT

The Scientific Instruments for the Large Space Telescope (LST) require a high degree of accuracy for positioning targets within their respective entrance apertures. The acquisition, verification of position, and guidance during an experiment must be accomplished with a minimum loss of observing time for the maximum effectiveness of the total mission.

This study evaluates several viable concepts and modes of operation that are applicable for a Target Acquisition and Positioning System (TAPS) that is responsive to the LST instrument requirements.

Section 1

INTRODUCTION

1.1 BACKGROUND

Since the inception of narrow slit spectrographs for astronomy, it has a concern not only to have the target within the entrance slit for an extended period of time but also that it is the desired target. In a space observatory, such as the LST, the problem is particularly acute because of the extreme need for the maximum cost effectiveness of the mission.

The problem has been addressed in prior space programs and in the first two LST Scientific Instrument study programs. The large scope of the LST Scientific Instrument study did not allow specifically for the in depth evaluation of the potential and ramifications of a target acquisition and positioning system's impact on the LST mission. Consequently, Goddard Space Flight Center awarded this contract (NAS 5-30700) for a comprehensive feasibility study to evaluate concepts, limitations, and parameters for acquisition, verification, and maintaining a target in a spectrograph entrance slit.

1.2 GUIDELINES AND OBJECTIVES

The guidelines for the Target Acquisition and Positioning System (TAPS) study were established from two prime sources: GSFC General Specification 5-30700 and in-study participation of NASA GSFC personnel. The major guidelines are summarized in the following paragraphs.

The objective of target acquisition is to position and maintain the target image within the individual instrument aperture with the minimum loss of observing time even in the presence of a moderate guidance instability. Thus, this function should be accomplished within a ground contact time, and the TAPS should be capable of functioning as an auxiliary guidance system. Open and

closed loop (those involving man) methods should be investigated and the advantages and disadvantages of both determined.

The verification of the target identity should consider utilizing automatic go-no-go type recognition methods and methods which involve the transmission of the scene to the ground.

As secondary objectives, the TAPS should be evaluated as a back-up camera system and consider its ability to track non-stationary targets. For both the main and secondary functions data handling and exposure control will be analyzed.

An evaluation of TAPS to function with a target star in the presence of bright neighbors is to be provided with relative brightness and angular separation as parameters.

Generic types of sensors are to be studied in the TAPS configuration in order to assess their influence on the TAPS system, Scientific Instruments and LST mission time profiles.

In all cases studied, suitable tradeoffs of field of view, F number, signal/noise, etc., will be made to optimize the systems and an attempt to achieve a dynamic range of 15 magnitudes (10^6) will be undertaken.

1.3 STUDY APPROACH

One of the first steps in the study was to consult with ground-based and space astronomers, to provide a background and a practical base for the study, to determine the observatory practices currently in use and astronomer preferences, and to subject the preliminary concepts generated to constructive criticism. The information gathered was used as a guide for the operational mode studies and to assess the role of the astronomer and automatic equipment in various functions such as acquisition, guiding on moving targets, etc.

As a result of the IDT team studies, the functional requirements that each instrument would impose upon the TAPS system were

made available. These included field of view, slit size, magnitude range and the faintest target that the instrument will view.

Operational mode concepts were generated, and tradeoffs involving instrument complexity, required equipment, time, impact of spacecraft capabilities, interface problems, etc., were made for various type targets. As a result of the tradeoff studies, recommendations were made as to the strengths and weaknesses of each mode, and its suitability for various kinds of targets and operations.

Functional concepts for acquisition, verification, track and guidance were generated, and analyzed with respect to required time, S/N desired, field of view, data handling requirements, background allowable, and so forth. It became apparent early in these analyses that the sensor would have a major impact. Therefore, the sensors were divided into generic types, and the studies were made for each generic type. It is felt that the information generated in this fashion is more useful than if the studies had been done for a particular sensor, such as a return beam vidicon.

During the period when the aforementioned efforts were being carried out, several meetings with NASA/GSFC personnel were conducted. At these meetings, the progress to date, the concepts and analyses were reviewed. Additional new inputs to the study effort were supplied, and the redirection of effort was made where necessary.

As a result of the study effort, concepts have evolved and been analyzed, and the results tabulated (for the four generic sensor types) for the functional concepts. Recommendations are made in the analysis sections, and are summarized at the end of the report. These recommendations involve the concepts and modes best suited to an application, and the generic sensor type most desirable for the TAPS application.

Section 2

SUMMARY

The primary function of the Target Acquisition and Positioning System (TAPS) is to acquire a pre-selected target (within a 25 μrad field of view) and position it in the center of a spectrograph entrance aperture. It is also capable of generating position error signals and transmitting them to the space craft guidance system. The spacecraft guidance system can utilize these signals to maintain the target in the center of the aperture.

2.1 OPERATIONAL CAPABILITY

The basic operation of TAPS may be understood with the aid of Figures 2-1, 2-2 and 2-3. It is assumed that the spacecraft will point the telescope to within 5 μradians of the target. The 25 μrad field of view containing the target is imaged on a suitable sensor as shown in Figure 2-1. The sensor divides the field of view into selectable size scan areas (i.e. - abjk) and measures the amount of energy on each scan area. The method of scanning is shown in Figure 2-3. This operation which yields coarse position information of the target will be referred to in this report as "Search Mode".

When the coarse scan area which contains the target has been determined (in this case cdhj), it is broken into smaller sub areas by scanning the sensor as shown in Figure 2-2. The result of scanning these smaller sub areas and measuring the energy from each area is used to determine the position of the image. This operation is referred to as the track or centering mode in this report.

In addition to the basic acquisition and track modes, several guidance concepts have been developed using the TAPS system, and the application of the TAPS system to field photography has been studied.

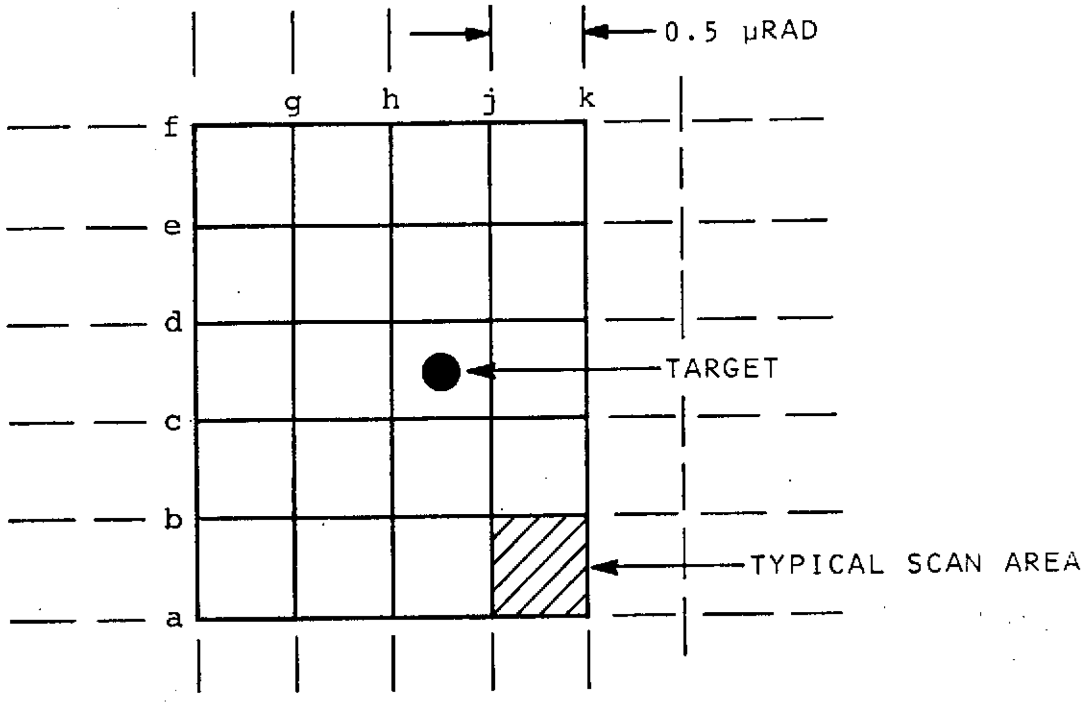

Figure 2-1. Acquisition of Target

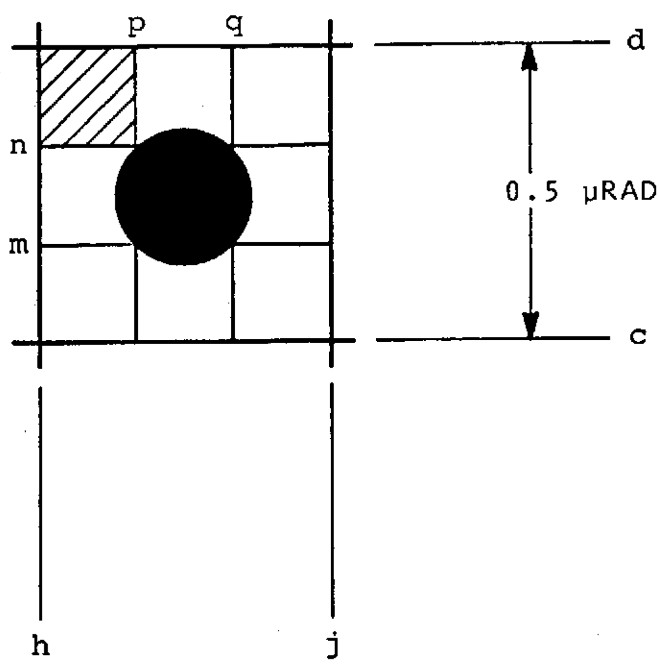

Figure 2-2. Determination of Target Position

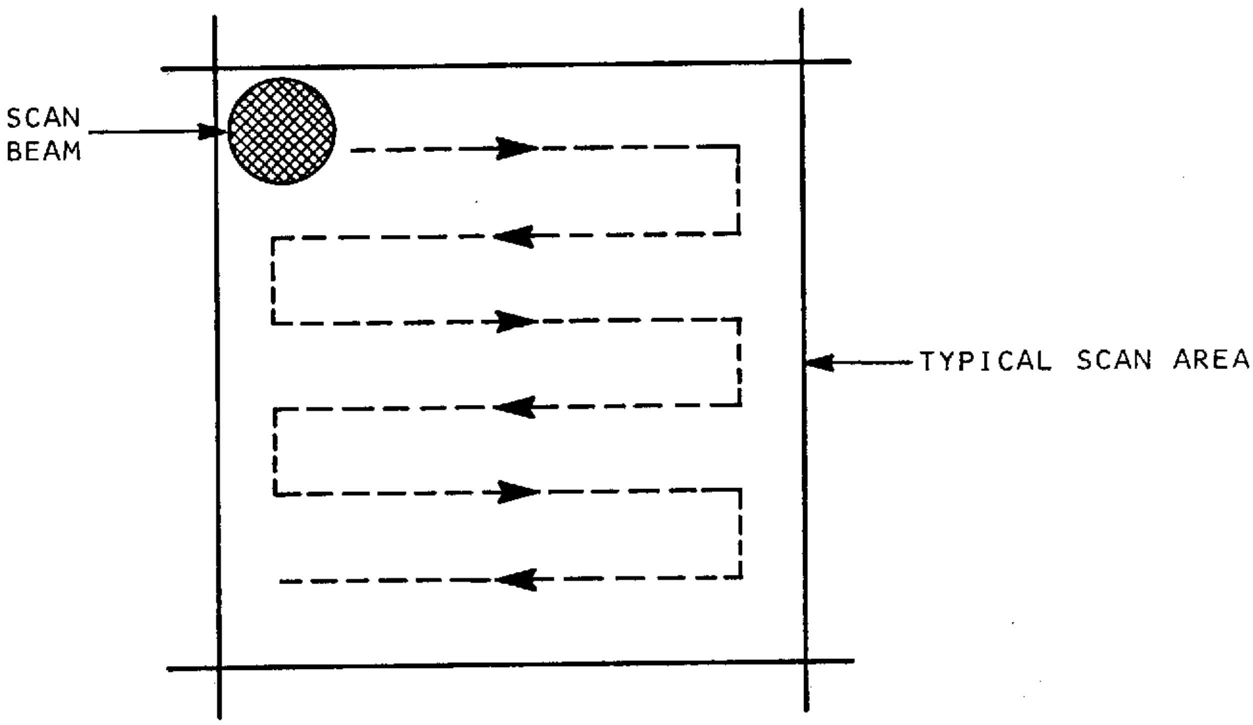

Figure 2-3. Sensor Scan Method

2.1.1 Capability

The versatility and usefulness of the TAPS System has been enhanced by providing the astronomer a selection of operational modes. In the manual mode the operator independently commands acquisition, verification and slit centering of target from TV ground display of spectrograph entrance aperture. In the semi-automatic mode the astronomer may direct the search and track operations with the aid of automatic devices and computers that are available to him on the ground or on the spacecraft. It is reasonable that with certain target configurations some operations such as slit centering of the target could be more efficiently performed automatically while verification of target would be performed manually.

The astronomer can in cases of positionally known point sources separated by at least 2 μrad (function of magnitudes) use the automatic mode for the complete sequence of operations including slit guidance position error signals.

2.1.2 Advantages of the Multi-mode Capability

One of the chief advantages of the multi-mode capability is that it minimizes the time required to perform a given task in a given situation. For instance, if the target is a single isolated star, the search and track may be done automatically, which would take the least time. If the target were located in a dense field, an attempt to automatically do search and track would take a large amount of time, or perhaps never succeed. Using a semi-automatic or manual mode, the operator could become part of the loop, and minimize the time required.

Multi-mode operation results in equipment simplication because it permits man to be a part of the loop. Man is normally better able to perform complex pattern recognition tasks and make decisions on a great variety of patterns better than automatic equipment. He

has the ability to make judgements, learn from his experience with the equipment, and take into consideration the characteristics and limitations of the equipment. For instance, in determining if a particular scene is the correct one, he can examine it for the important features, and disregard those which he knows are not important. He may also have determined from past in-flight experience that tube noise is greater or less on a particular part of the sensor, and take that into account in determining the presence of an object. The presence of man also optimizes the operation, since he can use the mode or modes best suited to a given situation. His ability to make judgements and learn from experience with the system, should result in the highest quality data.

System reliability will be enhanced by a multi-mode operation, because the experiments may be completed in several ways, and all of which would have to be inoperable for the experiment to be unsuccessful.

The use of multi-mode operation reduces the amount of data handling required. It makes possible the use of maximum automation in a given situation, calling for the least exchange of information between ground and the S/C. It also permits the operator to transmit only that part of the total data gathered which he feels is necessary.

The operational capability of TAPS may be demonstrated graphically by the flow chart of Figure 2-4. This flow chart represents the case where the astronomer will depend upon S/C pointing to aim the telescope to within 5 μrad of the target. The search mode will be semi-automatic, and the centering automatic. The loop is entered at the top of the diagram with an acquisition command and the scene coordinates being transmitted to the spacecraft. The S/C slews to the commanded position, and transmits a search command to the TAPS system. The TAPS system searches a 25 μradian area by the method described in sections 2.0 and 3.2, finds the target, and transmits the coordinates of the scan area in which the target was found and a picture of the scene to the ground.

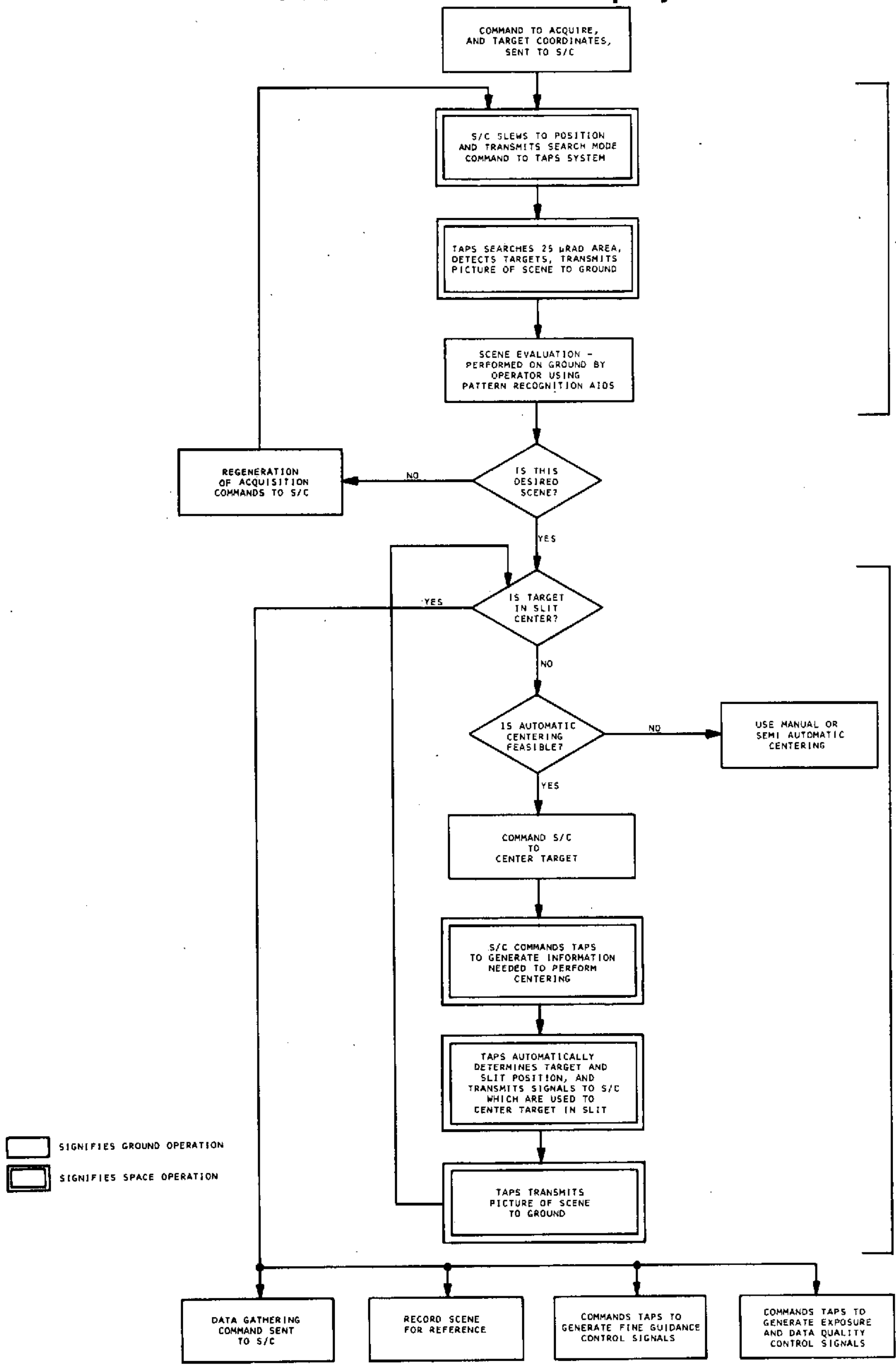

Figure 2-4. Typical TAPS Operation Flow Chart

The ground operator examines the T.V. data transmitted by the TAPS system, and verifies whether the scene displayed is the desired one. In this effort he is aided by automatic equipment such as image enhancers, and controls which simplify the presentation. If he determines that the scene presented to him is not the desired one, he must check on S/C position, pointing error, the correctness of the coordinates be transmitted to the S/C, etc., until he finds the source of the problem. Then he generates new acquisition commands and transmits them to the S/C.

Once the scene is judged to be the correct one, the operator must decide if the target is centered in the slit, which will almost never be the case at the end of the search mode. The next step is decide if automatic centering is possible. Since it had been decided to use automatic centering, the operator now transmits a centering command to the S/C. The S/C in turn commands the TAPS to generate error signals which may be used to center the target in the slit. TAPS goes into its automatic centering mode as described in sections 2.1 and 3.3, determines the coordinates of the slit center and the target, and transmits signals to the S/C which are used by the S/C to center the target in the slit. When the target has been centered in the slit, TAPS transmits a picture of the scene to the ground, and data concerning the slit and target positions.

The operator examines the picture of the scene and TAPS data regarding the slit and target positions, and verifies that the target is centered. If it is, the picture of the scene is recorded for reference purposes, and instructions are transmitted which result in spectrograph data gathering, and the generation by the TAPS system of fine error, exposure and data quality control signals.

If the operator concludes from the TAPS evidence that the target is not centered in the slit, he must again decide if automatic centering is feasible. If the answer is yes, he again commands automatic centering. If the answer is no, he must then change the mode to manual or semi-automatic.

2.2 FUNCTIONAL CAPABILITIES

The TAPS functional capabilities are dependent upon the sensor type. For this reason, the various concepts and techniques embodied in this report are studied for each of four generic sensor types. The first is a high gain non-integrating sensor which has a fixed aperture. The size of the aperture limits the area of the tube which can receive energy. The second is a high gain non-integrating type which doesn't have an aperture, and can gather data over its entire photocathode area. The last two are integrating types; one with moderate electron gain and low target dark current, and the other with high electron gain and relatively large target dark current. The functional characteristics will be discussed in this section for an integrating type sensor which has the best overall characteristics for the TAPS application. Later in the report, in sections 4.2 - 4.8, the capabilities of TAPS are discussed for four sensor types.

- Using TAPS, it is possible during search mode to find single target of 23rd magnitude or brighter, and transmit a 25 μrad square picture of the scene containing the target to ground for verification.

- Search may be accomplished in less than 10 seconds with a probability of automatically finding a single $23m_V$ star of 98%, if the background is uniform at 20th magnitude/$\widehat{sec}^2$. The probability of false alarm under these conditions is 0.1%. If the background is 23rd magnitude/$\widehat{sec}^2$, a neighboring star 5 magnitudes brighter must be at least 0.13 $\widehat{sec}$ from the target star, when the target is centered in the sensor scan. A memory is not required because the sensor is capable of storing the search mode picture, and about 25000 bits of data are required to transmit the picture to ground.

- Track is the furnishing of information (a picture) for the purpose of (1) centering the target in the entrance slit of the instrument, and (2) verification of centering.

Track may be accomplished in less than 15 seconds, against a uniform background of 18th magnitude/$\widehat{sec}^2$, for a 23rd magnitude target. If the uniform background is 23rd magnitude/$\widehat{sec}^2$, a neighboring source 5 magnitudes brighter must be at least 0.134 arc sec from the target star. During track, if a 6 μrad square picture is transmitted to ground, about 25,000 bits of information are required.

- The TAPS system is capable of functioning as an auxillary guidance system. During the study, four methods or concepts for automatically or semi-automatically achieving this purpose were developed. One of the more likely candidates is described in paragraph 4.5.4. If this is implemented, 1.2 minutes are required to detect an image shift of 0.005 arc seconds, (one-tenth the airy disc diameter at 300 nm) in the position of a 23rd magnitude star, against a uniform background of 23rd magnitude/$\widehat{sec}^2$. The astronomer or operator may elect to transmit the guidance information/a picture of the scene to the ground. To do this 25,000 bits are required for a 6 μrad square picture. No memory is required for the picture, since it is stored on the sensor.

The preceeding paragraphs have outlined the TAPS functional capabilities for sensor III, for the search, track and guidance modes. Table 2-1 is a concise summary of those paragraphs. Later in this report, Table 4-1 summarizes the TAPS capabilities for the search track and guidance modes, for all four basic sensor types.

Table 2-1. TAPS Functional Capabilities

Mode	Parameter	Quantity
Search	Number of Elements 25 μrad Field	3906
	5 μrad Field	156
	Number of Bits 25 μrad Field	23436
	5 μrad Field	936
	Elapsed Time	5.4 sec
	False Alarm Rate	0.001
	Acquisition Probability	0.98
	Limiting Background $m_v\ \widehat{\text{Sec}}^{-2}$	20
Track	Elapsed Time	14 sec
	Limiting Background $m_v\ \widehat{\text{Sec}}^{-2}$	18
Guidance	Elapsed Time	1.2 min
	Limit Background $m_v\ \widehat{\text{Sec}}^{-2}$	23

NOTE: A memory is not required for the sensor used for this summary.

Section 3

CONCEPTS AND IMPLEMENTATION

3.1 OPERATIONAL MODE CONCEPTS

3.1.1 Pattern Recognition

The basic approach is that of taking a picture of the scene surrounding the target and comparing it with a picture from the high resolution camera or a finder chart prepared by the astronomer. Comparisons are made, and a decision is made as to whether the target is the desired one. After verification is made, the pattern of the field may be used to guide the target to the center of the slit. The basic technique may be implemented with either the manual, semi-automatic or automatic modes.

3.1.2 Spacecraft Pointing Directed

The spacecraft pointing system will initially direct the target to the instrument entrance aperture. Any observation that requires positioning of the target to better than 5 μradians (spacecraft pointing accuracy) relative to the instruments entrance aperture should utilize the TAPS. The spectrographs may select entrance aperture sizes over 25 μradians in which case the TAPS system will not be needed or useful and spacecraft pointing accuracies will suffice. Spacecraft pointing and target positioning requires prior information of the relationship of the target and a reference star, and the relationship of both with respect to the entrance aperture. Utilizing TAPS, these relationships must be known to 5 μradians to center the target to one tenth of the image diameter at 300nm. Without TAPS, the relationship must be known to 0.025 μradians.

3.2 ACQUISITION AND VERIFICATION (SEARCH) CONCEPTS

The search area of the sky is imaged on a suitable sensor and areas of the sensor corresponding to sections of the sky are scanned out as shown in Figure 3-1. When the photoelectron level of one of the sensor scan areas exceeds a threshold, an acquisition signal is generated, and a picture of the search area is made available for ground readout.

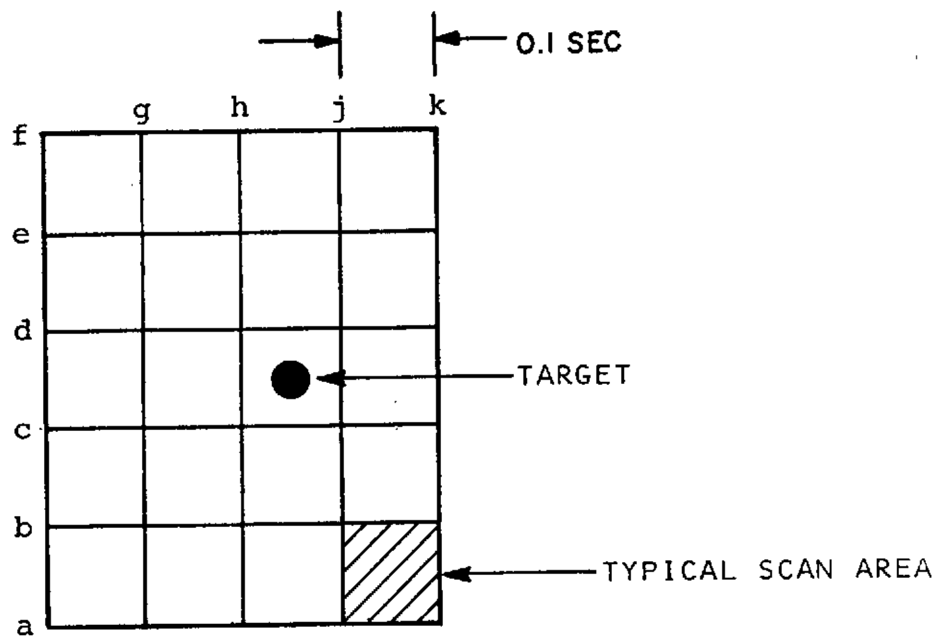

Figure 3-1. Target Search

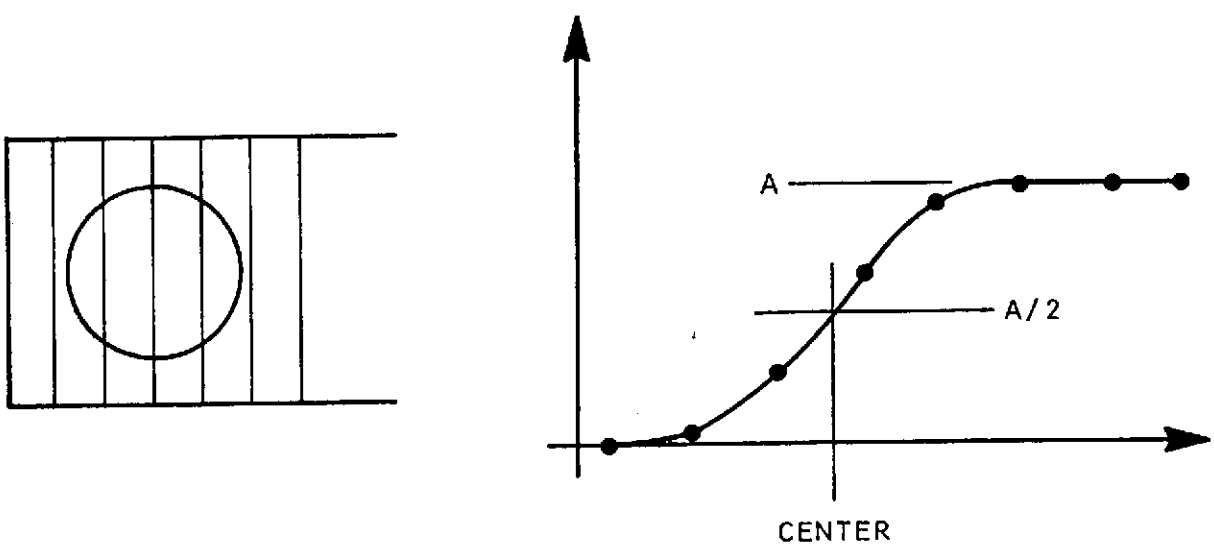

Figure 3-2. Target Centering (Track)

If there are two targets within the field separated by less than 0.1 arc seconds, they may be separated by several methods. For example, the position of the sensor scan areas could be shifted up/sideways by some fraction of 0.1 arc seconds until each star is on a different sensor scan area, which would separate them. A second method is to use a smaller sensor scan area, such as 0.03 arc seconds. A third method is to use a smaller sensor scan area, and shift the position of the scan areas.

3.3 TARGET CENTERING (TRACK)

Refer to Figure 3-2. The sensor scan area in which the target is found is broken into smaller scan areas. A plot or profile of the total photoelectron count as a function of scan area is made. The point at which the p.e. count is 50% of maximum is taken as the center of the image. Assuming that the center of the slit is known, the target is moved a distance equal to the difference in position between the slit and target centers.

3.4 GUIDANCE CONCEPTS

I. The target is moved some distance "d" from the slit as shown in Figure 3-3. The target centering mode is then activated, and used to bring the target to the slit center.

II. The area on the slit jaws adjacent to the image is monitored for a period of time as shown in Figure 3-4. If the difference in the signals from the slit jaws exceeds a predetermined limit, an out of specification condition is indicated. At this point, guidance concept #1 is employed to return the image to center. This method, like method #1, will work whether the image is larger or smaller than the slit jaw.

III. This concept assumes the image is definitely contained within the slit jaw. The areas of the slit jaw are monitored for a predetermined period of time, and the resultant error signal is used to calculate the desired correction to center the image. The amplitude of error will be used to determine the displacement.

IV. See Figure 3-5. The image is assumed larger than the slit jaw. This could be a focussed image which is larger than the slit, or a deliberately defocussed image. The imbalance in the spillover energy signals is used to correct the image position.

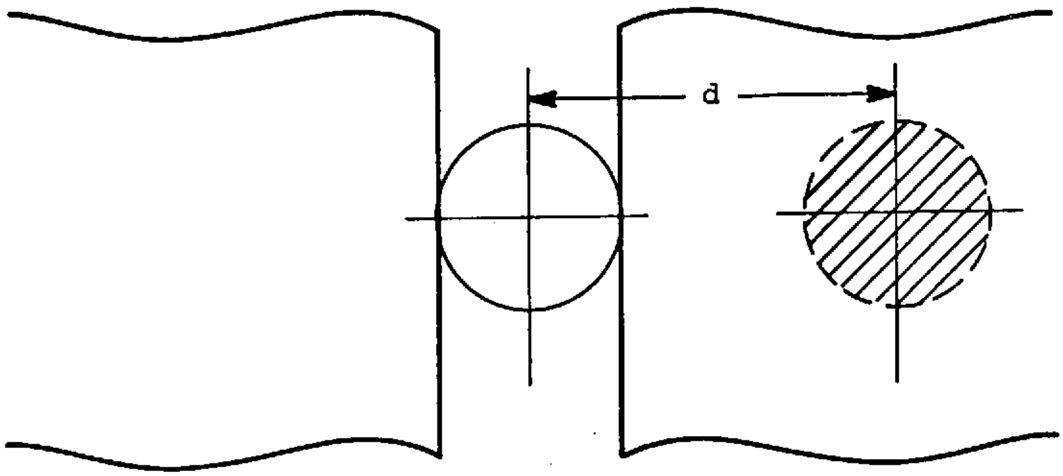

Figure 3-3. Guidance Concept #1

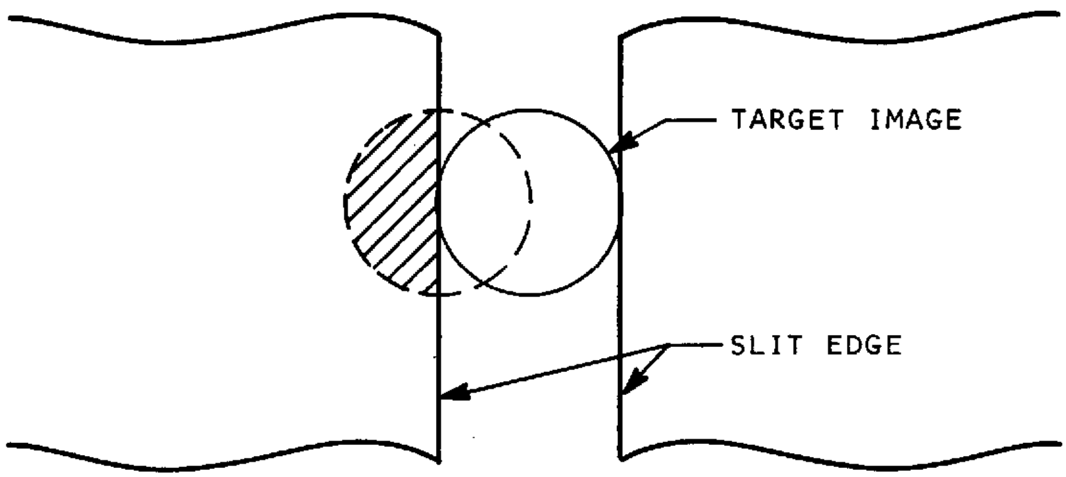

Figure 3-4. Guidance Concepts #2 and #3

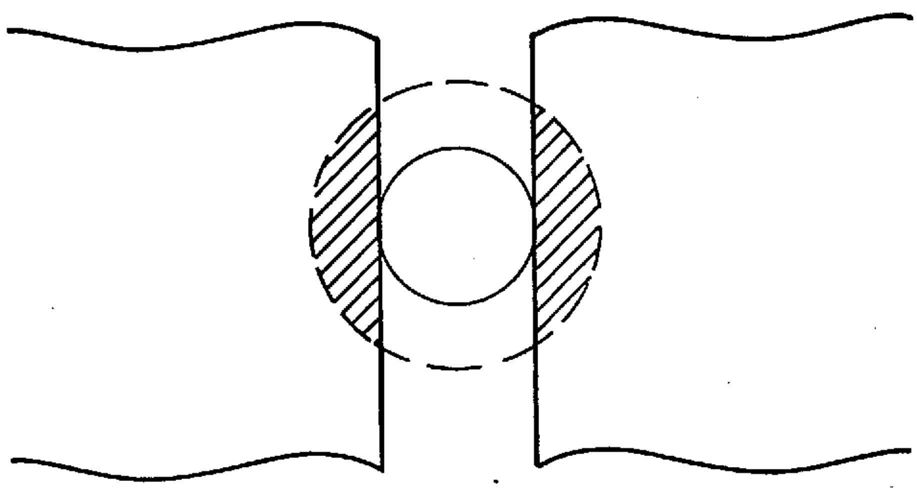

Figure 3-5. Guidance Concept #4

3.5 NON-STATIONARY TARGET TRACKING

For fast moving targets, automatic TAPS will only work where there is a high contrast feature such as a bright spot or a limb of the object. In this case, the centering concept, or one of the guidance concepts which can be automatically implemented may be used. In such a case, the high contrast feature would not have to be centered, but could be kept in a fixed location with respect to the spectrograph entrance slit. This permits the centering of a low contrast feature as follows; the low contrast feature (target) must be separated from a high contrast feature by an angle less than 1/2 the TAPS field of view. The high contrast feature is offset from the slit center by an angle equal to its separation from the low contrast feature. If the TAPS tracks the high contrast feature at this fixed offset, the target feature will remain within the slit.

For slowly moving targets, large targets with low contrast features may be tracked using semi-automatic or manual modes of operation of acquisition or centering. However, operation is limited to the time the S/C is in contact with the ground. Slowly moving targets with high contrast features may be tracked using the centering or guidance techniques.

3.6 EXPOSURE CONSIDERATIONS

Exposure control falls into two categories. The first is determining the optimum time to expose the spectrograph to the target energy, so that the desired signal to noise ratio is achieved, and sensor saturation avoided. The second is to determine the amount of time that the target is within the slit, so that guidance problems or occultations will not result in improper exposure.

3.6.1 Exposure Determination

The TAPS system and the spectrograph may be calibrated (both pre and post launch). This knowledge, coupled with the use of several filters which will yield a rough spectral distribution of

the target, and prior examinations of the target with the field camera, will provide the inputs from which an exposure time calculation may be made. The filters can be part of the TAPS system, or they can be located elsewhere, such as in a field camera. The calculation may be made on the ground or the S/C.

Another means of determining the desired exposure time is to perform a rough calculation of the required exposure time either from a prior knowledge or the method outlined above. When 30-50% of this time has occurred, the spectrograph can be read out, if the read noise is not excessive. The results can then be used to obtain a precise calculation of the desired exposure time.

3.6.2 Exposure Quality Monitor

One of the guidance concepts, such as Concept #4, can be used to determine the position of the star relative to the slit. This measurement may, if desired, be performed every 1.2 minutes. A profile of target vs. slit position may be stored in a memory if desired and transmitted to ground to aid in data reduction. It will also be used to determine the time that the target is within the slit.

3.7 SLIT CENTER DETERMINATION

a) Concept I - The slit is back illuminated with light equivalent to a bright star, and the light is imaged on the sensor. Suitably small sensor scan areas are read out, and the scan readout pattern shown in Figure 3-6 and the equations given in Section 4.6,1 are used to determine the slit center.

b) Concept II - The slit jaws are illuminated and the approximate slit center determined, as in (a) above. The location of the sensor scan area is shifted until the readout is one-half that obtained when the sensor scan area is 100% on the slit jaw as shown in Figure 3-7. This position corresponds to the edge of the slit jaw. Once the location of edges are established, the center may be determined.

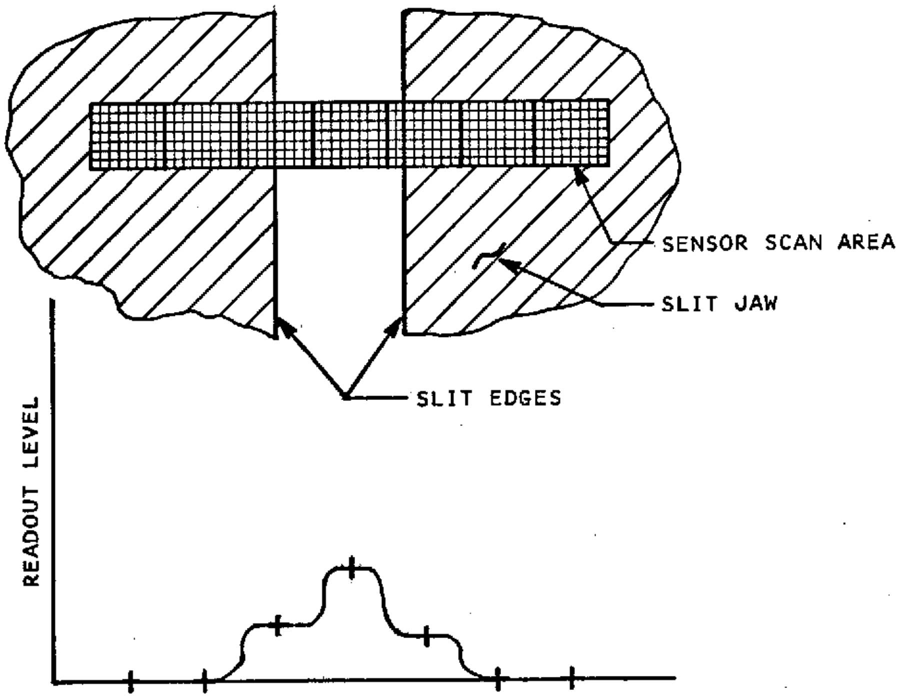

Figure 3-6. Slit Center Determination #1

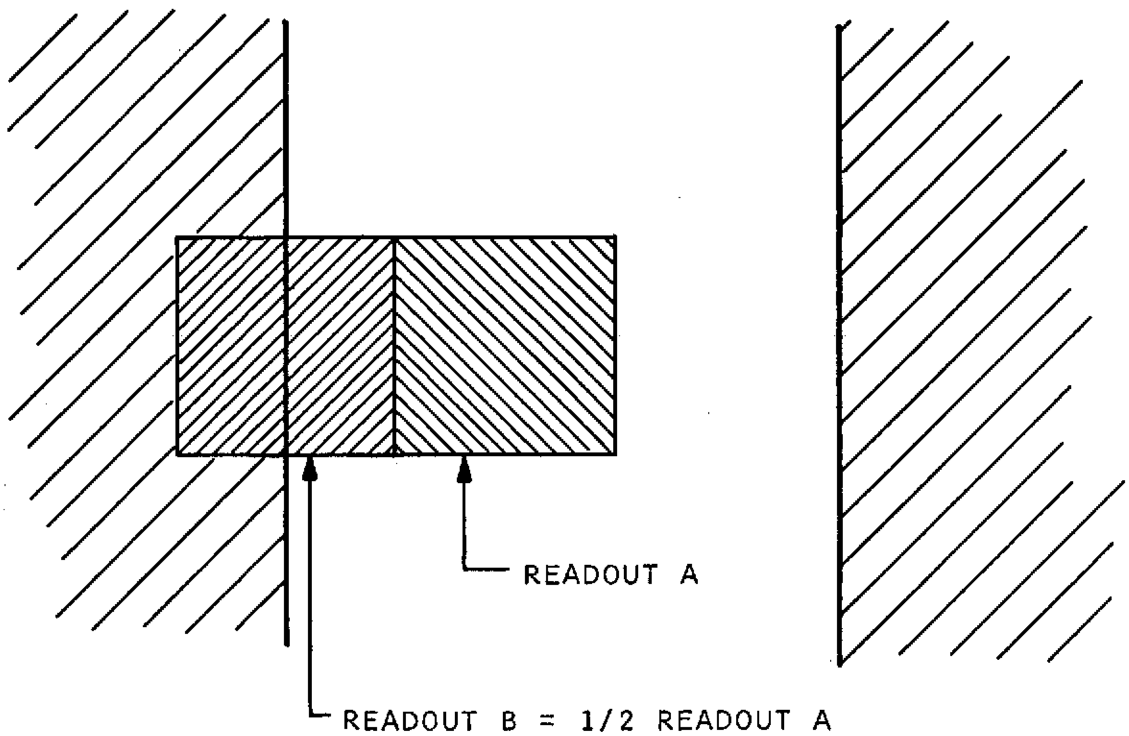

Figure 3-7. Slit Center Determination #2

c) Concept III - The slit jaws are illuminated uniformly as shown in Figure 3-8, and an intensity profile of the 50 micron sensor scan areas used to determine the approximate location of the slit center. The position of the sensor scan area is then shifted some fraction (say 0.2) of the slit width at a time and another photoelectron vs. position profile is made. The resultant profile may then be used to establish the slit center, since the profile is symmetrical about the slit center.

d) Concept IV - Fiducial lines about 10 microns wide are scribed or frosted as shown in Figure 3-9. Lambertian scattering is used to determine the position of the fiducial lines, and the relationship of the fiducial lines to the slit center is used to determine the slit center. This technique is illustrated for a pinhole, but is applicable to slits also.

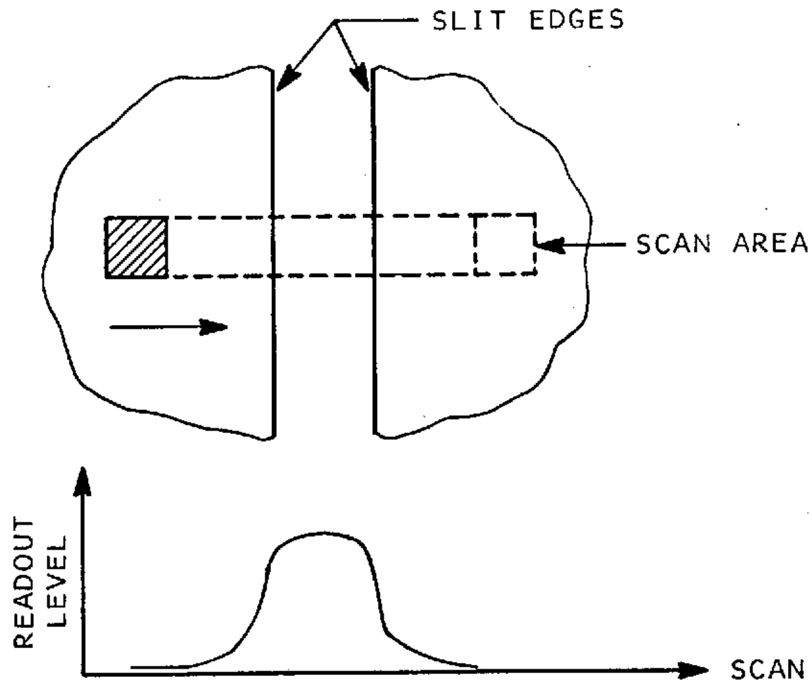

Figure 3-8. Slit Center Determination #3

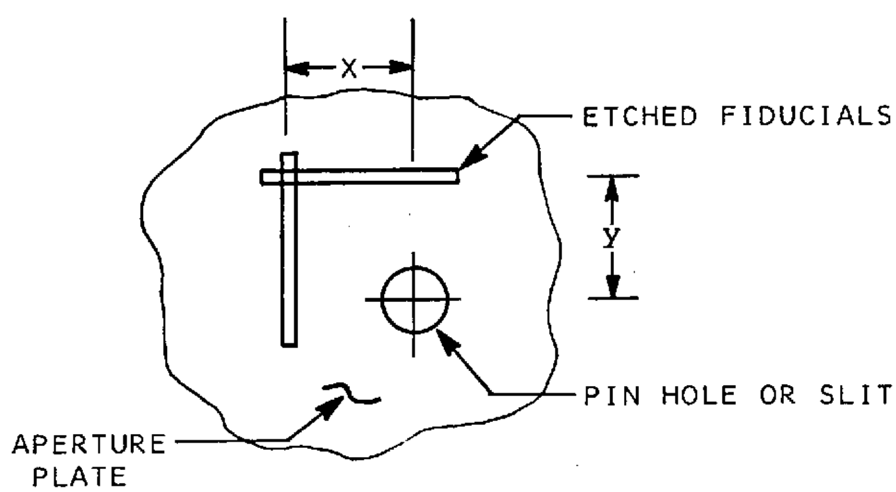

Figure 3-9. Slit Center Determination #4

Section 4

SYSTEM ANALYSIS

4.1 MODE ANALYSES AND CONSIDERATIONS

4.1.1 Pattern Recognition

It is possible to perform automatic pattern recognition for easily recognized target patterns with a few easily distinguishable features. As the patterns become complex, or the features possess smaller and smaller contrasts, the pattern recognition task becomes more difficult. The automatic device must be capable of a good deal of flexibility to deal with many target types, and must possess a certain amount of judgement to discern signals which are not much greater than noise, or to reject information which is caused by equipment imperfections. Under these conditions, the automatic equipment must possess the judgement, learning ability and flexibility of a man. This does not appear to be feasible at this time. For complex targets, man, or man in conjunction with character-recognition aids, must be part of the loop. For these reasons, except for simple targets, pattern recognition is best suited to the manual and semi-automatic modes.

Scene verification is by definition a pattern recognition task, and the verification function is therefore best performed by pattern recognition. It should be noted at this point that pattern recognition involves not only the geometric distribution of the objects in the scene, but a measurement of their intensity as well.

It is desireable to perform the tracking and guidance functions automatically which means that for objects such as stars or targets with high contrast features, pattern recognition is not recommended.

However, on complex targets such as clusters or those lacking high-contrast features, automatic tracking devices become impractical and pattern recognition tracking or guiding techniques are the best.

4.1.2 Spacecraft Pointing Directed

This concept defined in Section 3.1.2, depends upon accurate information about the relationship of the target and guide object, and accurate S/C pointing. The S/C pointing accuracy is 5 μrad. Thus, a pointing directed centering will not center a 3000Å diffraction limited image to within 10% of its Airy Disc diameter. The acquisition field of view is 25 μrad, and the use of S/C pointing to place the target within the TAPS acquisition field is excellent because it is automatic, fast and more accurate than necessary. It also provides a means of tracking moving targets when the S/C is not in contact with the ground station. It may also be combined with other concepts to provide centering of targets not suitable to automatic tracking, when not in ground contact. For example, semi-automatic centering of a star cluster could be done while the S/C is in contact with the ground, and the S/C stability (0.025 μrad) used to maintain the centering when out of ground contact.

4.1.3 Manual, Automatic and Semi-Automatic

These modes are defined in Section 2.1.1. A completely manual mode requires the simplest equipment but is the least accurate, requires ground contact, and is more time consuming. Therefore, a completely manual TAPS operation is not recommended as practical or efficient.

A completely automatic TAPS is very efficient, but is not practical to accomplish for the variety of targets which the TAPS will be called upon to center. Furthermore, some astronomers would prefer to perform the verification functions.

The semi-automatic mode permits the operator to participate in the operation to the degree which he thinks is optimum for the experiment. This flexibility will enable him to make the maximum use of automated modes and equipment, consuming the least amount of time. This is demonstrated in the flow chart of Figure 2-1, where the verification function is performed by the operator (aided by image enhancers and presentation simplifying devices) and the centering is done automatically. It also enables him to alter the experiment sequence of the degree of automation during an experiment. A drawback of the semi-automatic mode is that it requires a more highly trained operator than a completely automated mode, but this would seem to be a minor consideration. Therefore, it is recommended that the semi-automatic mode be employed the majority of the time.

4.2 PARAMETER STUDIES

4.2.1 Input Assumptions

Section 1.2 mentioned the guidelines which were given the start of the study. In addition to these guidelines, other assumptions had to be made in order to give meaning to the study. These inputs and assumptions are listed below:

- Large-field work already accomplished.
- Required Search Area - 25 μrad square.
- Minimum electron beam position errors - 8 micrometers.
- Minimum intensity differentation, one magnitude for automatic search operation.
- Four basic detector types.
- Temperature 20°C.
- Photocathode dark current, 4.0 p.e. mm^{-2} sec^{-1}.

- Target must be centered within ground contact time ≈ 10 minutes.
- Target dark current type IV[1] referred to photocathode
  3×10^3 p.e. mm^{-2} sec^{-1} @ -40°C
  2×10^5 p.e. mm^{-2} sec^{-1} @ +20°C
- Target - 23rd magnitude minimum.
- Sky background - uniform at 23 mag/$\widehat{sec}^2$.
- Target (point source) must be centered to 10% at a diffraction limited 3000Å Airy Disc.
- Slit center is reference.
- Photoelectron Counting Efficiency 50%.
- 25 μradian picture of scene desired.

4.2.2 Focal Length

If the electron readout beam of the sensor is focussed at a point other than the commanded position, an error in the true position of the target results. The position of the electron beam in the sensor corresponds to a position in the TAPS object plane.

Electron beam errors are caused by power supply drifts, change in earth's magnetic field, electron focus change, etc. Presently, it is estimated that for the TAPS application, the electron-beam error is 8.2 micrometers.

Assuming that the electron-beam error is set equal to the error in determining the image center, and that they root sum square, the beam position error may be set equal to 70% of the specified error.

The specified error is 10% of a diffraction limited Airy Disc diameter at 3000Å, therefore the beam position error must be equal

(1) Report to LST Steering Group, J.J. Lowrance and P. Zucchino, Sept, 1971, p 16.

to or less than 7% of an Airy Disc diameter at 3000Å. The angular subtense of the Airy Disc diameter is 2.44 λ/D in radians, thus

beam error,

$$\varepsilon_{beam} = 0.07 \times 2.44\ \lambda/D$$

$$= 0.07 \times 2.44 \times \frac{3000 \times 10^{-10}\ m}{3m}$$

$$= 1.71 \times 10^{-8}\ \text{radians}$$

Since this angle must equal 0.0082 mm of beam error

$$r = \frac{S}{\theta} = \frac{82 \times 10^{-7}}{1.71 \times 10^{-8}}$$

$$r = 480\ \text{meters}$$

For a 3 meter telescope $f\# = \frac{480}{3} = 160$

Since the telescope is assumed to have an f# of 24, the TAPS requires an optical multiplier of 6.7.

It is desirable to cover a 25 μradian field of view with the TAPS system. The width of the image tube for a 480 meter focal length equals (25×10^{-6}) (480) or 12 millimeters.

4.2.3 Sensor Types

The performance of the TAPS system, and the implementation of the concepts for search, track, and guidance, are a function of the sensor used. Paragraph 4.3.1 illustrates one way in which the sensor affects a system parameter such as f number. It also impacts resolution, dynamic range achievable, time required to perform an operation, data handling capacity, temperature control requirements and memory requirements.

By studying system performance as a function of various sensor types, three things are accomplished:

1) The strengths, weaknesses and future potential of various types of sensors are revealed for the different concepts.

2) An insight is obtained into the requirements of sensor improvement for a given concept.

3) Study procedures are established, such that the effect on the different aspects of system performance can be evaluated against system parameters.

The four sensor types evaluated are listed below:

I. Non-integrating, very high internal gain, reads out entire photocathode area. Needs an aperture (internal or external) to control and position a selected photocahode area.

Examples: Photomultipliers and Image Dissectors.

II. Non-integrating, very high internal gain, with scan that reads out a small area of the photocathode.

Example: Channel multipliers, "ideal" photon counting tubes.

III. Integrating, low to moderate internal gain with scan that reads out a small area of the photocathode.

Examples: Vidicons and SEC vidicons.

IV. Integrating, high internal gain, with scan that reads out a small area of the photocathode.

Examples: SIT, EBS, RB vidicons.

4.2.4 Effect of Low Photon Rates

The faintest point source target that the spectrograph is expected to examine is 23rd magnitude. The response to an A0, 0.03 magnitude star has been measured at 8.03×10^{-14} amperes per square centimeter of effective collecting area.(1) For a 3 meter telescope with 50% diameter obscuration, where 0.625×10^{19} electrons/sec equals 1 ampere, while observing a 23rd magnitude star, is equivalent to 17.3 photoelectrons/second.

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(1) Stellar Photometric Data for Six Different Photocathode Materials and the Silicon Detector, F.F.Forbes and R.I.Mitchell, University of Arizona, 1968.

As a result of the low photoelectron rate, analog scan techniques used for automatic centering require very low information bandwidths (0.04 Hz) to overcome the effects of phenomenon such as amplifier noise, rendering them impractical. Also, as will be shown later in this report, for concepts which employ the use of partial images, sky background and tube dark currents become comparable to the signal. The result of this is problems with false alarms and the requirement for longer time periods to accomplish the TAPS function.

4.3 SEARCH MODE ANALYSIS

The search mode concept is to scan sensor sub-areas corresponding to a section of image space (Figure 3-1) and measure the photons impinging upon this area. Since a resolution of 0.1 arc second or better is desired, and the scale factor at f/160 is 0.48mm/μrad (≈2400 μm/arc sec), a sensor scan area of 0.2 millimeter square will be used. For a scan area of this size, the spreading of the image by the tube MTF may be neglected.

4.3.1 Sensor I

For this sensor and a 23rd mag/$\widehat{\sec}^2$ background, the dark current and background are not a problem. Because of the very high internal gain, amplifier readout noise is negligible. Therefore, false alarms may be neglected. Since it is desireable to differentiate between stars of one magnitude difference, about 10 total photoelectrons minimum must be counted. For a 23rd magnitude target producing 17.3 photoelectrons per second, 8.6 pe/second are counted, and 1.2 seconds per elemental .2 mm square area is required. The scale factor is 0.48 mm/μrad, if a 5 μrad field is used for the search mode, $\left(\frac{5x.48}{.2}\right)^2$ = 144 readouts must be performed in sequence because sensor I has no storage capacity. The time required is 173 seconds. For a picture of the entire 25 x 25 μradian field, 72 minutes are needed.

For a 23rd magnitude/$\widehat{sec}^2$ background, and a 0.22 mm square search area, the p.e. count is 0.14 p.e./sec. The dark current is 0.18 p.e./sec, which is negligible compared to the signal count of 17.3 p.e./sec. The background will not significantly affect the false alarm rate if the signal to background ratio is 8. If the background increases by a factor of 3 magnitudes ($\approx$ 16), it will be about 2.24 counts/sec, which is about one-eighth of the signal count. The noise in the background will = $\sqrt{2.24}$ or 1.5 counts/sec, which yields S/N_B = 11.5, which has a negligible effect on the false alarm rate. Therefore, the background may be 3 stellar magnitudes brighter during automatic acquisition.

If the background increases by 2 additional magnitudes, $N_B = \sqrt{2.24 \times 6.25}$, and $S/N_B \approx 4.5$. If a S/N_B of four will suffice with man being part of the verification loop, then about two magnitudes may be added to the background, making the limiting magnitude 18th/$\widehat{sec}^2$. It should be noted that if more time is consumed, the S/N ratios will improve, and a brighter background is permissible.

To cover a 25 μradian square field about 12.5 mm square area is needed. Each sensor scan area is 0.2 x 0.2 or 0.04 mm^2, therefore, $\frac{(12.5)^2}{0.04}$ or 3906 elemental areas must be read out. If 6 bits are used to encode the photoelectron count in each area, a total of 23436 bits are required.

4.3.2 Sensor II

This type is similar to Sensor I except that it registers small elemental areas of the photocathode. The smallest area presently envisaged is 50 μmeters square. Four of these may be combined to yield a 200 μm square area for search. The entire tube gathers information simultaneously. Thus, 1.2 seconds (the time to achieve the proper S/N ratio on one element) is required for search. The sensor is non-integrating, which means that very rapid readout is required. Because the sensor has no storage, a memory is required

as in the case of the Type I sensor. All other parameters, such as data bits required and limiting background, are the same as for Sensor I.

4.3.3 Sensor III

This sensor integrates the incoming energy on a target and stores it there until it is read out by a scan beam. The smallest sensor scan area is assumed to be 50 μmeter square. Because of the integrating and storage capacity, no memory will be required for this sensor. For search mode, the scan will be made 200 μm square, therefore, the data handling bit count will be the same as for Sensor I.

Because the sensor readout is a scan beam current, a threshold must be set such that the noise in the readout amplifier will not cause false alarms*. Figure 4-1 depicts the problem graphically. The signal may be at a value of 0 (no target) or I_s (target present). The noise, which is assumed to have a gaussian distribution of density, will ride "on top" of the 0 or I_s signal. The threshold may be set at some value T_h. The probability of the noise for the "zero signal" condition exceeding the threshold is the cross-hatched area to the right of T_h. The probability of noise causing the output to go below the threshold when a signal is present is shown by the shaded area to the left of T_h. Figure 4-2 shows the total error probability as a function of S/N ratio for a threshold set at 1/2 the signal level.

For the TAPS application, the false alarm probability is selected at 0.1% which yields a T/N ratio of 3.08**. The acquisition probability has been set at 98%, which yields a S/T ratio of 2.05. The S/N required is therefore ≥ 6.3. For this sensor, dark

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* Information Transmission, Modulation and Noise, Second Edition Mischa Schwartz page 330-338.

**Handbook of Mathematic Tables and Formulas - Burrington.

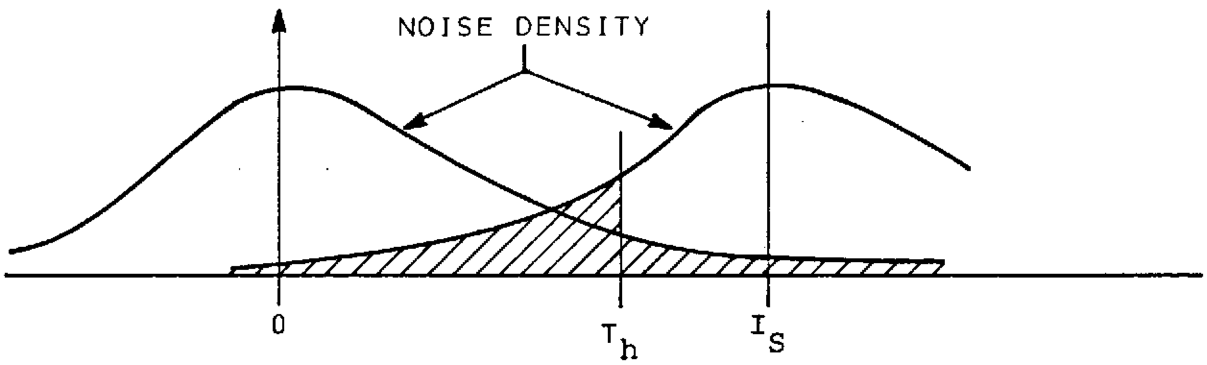

Figure 4-1. False Alarm and Acquisition Probability Considerations

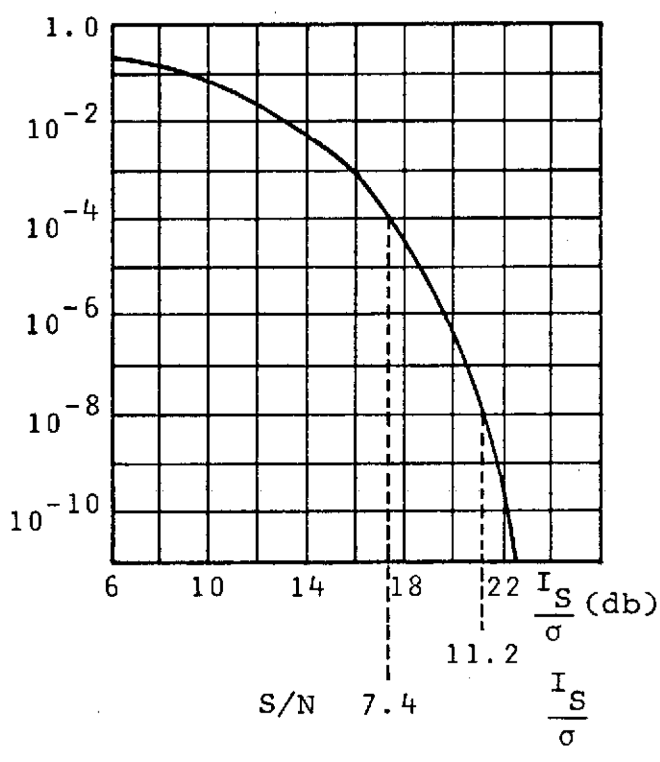

Figure 4-2. Total Error Probability

current is much smaller than full signal current, and the tube readout noise ($\sqrt{128 \text{ p.e.}}$) predominates. It may be shown that $S/N = S/\sqrt{S + 128}$ where S = signal p.e. For a S/N of 6.3, S = 94 p.e. The signal rate is 17.3 p.e./sec, therefore 5.4 seconds is required to perform acquisition, not including the time to read out the sensor.

If the ratio of signal to background noise of 20 ($S/N_B = 20$) is achieved, it will have a 10% effect on the overall S/N of 6.3, which is permissible. $N_B = \frac{94}{20} = 4.7$, Background $B = (4.7)^2 = 22$ p.e. per 5.4 sec = 4.07 p.e./sec. Compared to a 23rd mag/$\widehat{\sec}^2$ background (0.14 p.e./sec) 4.07 p.e./sec is a factor of 29 or about 3.5 magnitudes. This means acquisition is possible against a uniform background of 19.5 mag/$\widehat{\sec}^2$ in the automatic mode. While it appears that this sensor will operate against a brighter background than sensors I and II (20th in automatic mode), it should be kept in mind that sensors I and II used only 1.2 seconds of time per scan area. Had we used 5.4 seconds of time per scan area, sensors I and II could have worked against an even brighter than 19th magnitude background. The limiting background listed for Search Mode is for an exposure time of 10 seconds per scan area.

4.3.4 Sensor IV

The considerations for this sensor are the same as for Sensor III, except that the noise is due to target dark current. It may be shown that the exposure time (t) is

$$t = (S/N)^2 \left(\frac{R_s + \frac{R_D}{2}}{R_s} \right)$$

where R_s = rate of signal p.e. @ photocathode

R_D = rate of dark p.e. @ photocathode

S/N is desired signal-noise ratio for a S/N of 6.3, $R_s = 17.3$ p.e./sec, $R_D = 8 \times 10^3$ p.e./sec

t = 1071 seconds (18 minutes)

A type IV sensor with a target voltage of 4 volts and a target capacitance of 2×10^{-14} farads/mm^2 will saturate on its own dark current at the end of 160 seconds (2.67 minutes) during search mode. Thus, a memory and a data processing system which calculates the average charge on a sensor scan element is required. The sensor must be read out $\frac{18}{2.67}$ or 7 times. Table 4-1 summarizes the Search Mode considerations.

4.4 TRACK MODE ANALYSES

During this mode, the postion of the center of the target is determined with respect to the slit center. The diffraction limited 300 nm image has a diameter of 117 μm, or a little more than two sensor scan area widths. The position of the center of the image is determined by using a profile of the p.e. count vs. sensor scan area position as shown in Figure 3-2. It may be shown that the maximum error in the center position determination p, caused by an error in reading the p.e. count, δ , is given by

$$p = \frac{W_I}{2} \delta,$$

where W_I is the image width, independent of the number of readings taken. The rms error decreases as more samples are taken. For the TAPS centering, a sample width of 50 μ meter will be used.

Assuming that the beam position error and the error in the p.e. count root sum square, 70% of the total error may be assigned to each, and the error in the p.e. count may be 7% of W_I

$$\therefore \quad 0.07\, W_I = p = \frac{W_I}{2} \delta$$

$$\delta = 0.14 \text{ or } 14\%$$

TABLE 4-1. SUMMARY OF TAPS CAPABILITIES AS A FUNCTION OF SENSOR TYPES, SEARCH, TRACK AND GUIDANCE MODES

MODE	PARAMETER		SENSOR TYPES I	II	III	IV
SEARCH	NO. ELEMENTS	25μr FIELD	3906	3906	3906	3906
		5μr FIELD	156	156	156	156
	NO. BITS	25μr FIELD	23436	23436	23436	23436
		5μr FIELD	936	936	936	936
	ELAPSED TIME	25μr FIELD	1.2 HR	1.2 SEC	5.4 SEC	18 MIN
		5μr FIELD	2.83 MIN	1.2 SEC	5.4 SEC	18 MIN
	MEMORY REQ'D		YES	YES	NO	YES
	NO SENSOR TARGET SCANS		-	-	1	7
	FALSE ALARM RATE		0	0	0.001	0.001
	ACQUISTION PROBABILITY		1.0	1.0	0.98	0.98
	LIMITING BACKGND* m_v-$\widehat{SEC}^{-2}$		19.5	19.5	19.5	19.5
TRACK	NO. SENSOR TARGET SCANS		-	-	1	3
	MEMORY REQ'D (SPACECRAFT)		YES	YES	NO	YES
	ELAPSED TIME		1.5 MIN	28 SEC	14 SEC	7.8 MIN
	LIMITING BACKGND m_v-$\widehat{SEC}^{-2}$		20	18	18	18

* FOR ELAPSED TIME OF 10 SECONDS.

TABLE 4-1. SUMMARY OF TAPS CAPABILITIES AS A FUNCTION OF SENSOR TYPES, SEARCH, TRACK AND GUIDANCE MODES (CONT.)

MODE	PARAMETER	SENSOR TYPES I	II	III	IV
GUIDANCE CONCEPT #1	NO. SENSOR TARGET SCANS	-	-	1	3
	ELAPSED TIME	1.5 MIN	28 SEC	14 SEC	7.8 MIN
	MEMORY REQ'D	YES	YES	NO	YES
	LIMIT BACKGND m_v-$\widehat{SEC}^{-2}$	20	18	18	18
GUIDANCE CONCEPT #2	NO. SENSOR TARGET SCANS	-	-	1	-
	ELAPSED TIME	5.9 MIN	3.7 MIN	3.5 MIN	28 HR
	MEMORY REQ'D	YES	YES	NO	YES
	LIMIT BACKGND m_v-$\widehat{SEC}^{-2}$	23	23	23	23
GUIDANCE CONCEPT #3	NO. SENSOR TARGET SCANS	-	-	1	-
	ELAPSED TIME, TRACK & GUIDE	12.4M + 44M	1.6M +22M	1M + 12.5M	
	MEMORY REQ'D	YES	YES	NO	
	LIMIT BACKGND m_v-$\widehat{SEC}^{-2}$	23	23	23	
GUIDANCE CONCEPT #4	NO. SENSOR TARGET SCANS	-	-	1	108
	ELAPSED TIME	2.8 MIN	1.4 MIN	1.2 MIN	4.8 HR
	MEMORY REQ'D	YES	YES	NO	YES
	LIMIT BACKGND m_v-$\widehat{SEC}^{-2}$	23	23	23	23

4.4.1 Sensor I

Because of the high internal gain and low dark current

$$\delta = 0.14 = \frac{1}{S/N} = \frac{1}{\sqrt{n}}$$

$$n = 51 \text{ p.e.}$$

The counting efficiency is 50%, and it is possible that only half the image may fall within the aperture. Therefore the time required at each position $= \frac{51\text{ pe}}{1} \times \frac{\text{sec}}{17.3\text{ pe}} \times \frac{2}{1} \times \frac{2}{1} = 11.86$ seconds. The target is within the 200 μmeter aperture of sensor I, and 4 X positions maximum are necessary to determine the X coordinate of the target. When the X coordinate has been ascertained, 4 Y positions maximum are needed to determine the Y position. The total time required is 8 x 11.86 = 95 seconds.

The background limit for this mode (19.5 $m_V \widehat{\text{sec}}^{-2}$) is the same as for the search mode, since the aperture size is the same.

4.4.2 Sensor II

The operation is similar to the search mode, except that the size of the sensor scan element is 50 μmeters and image spread caused by the tube is no longer negligible. The 50 μm scan area reduces the background by a factor of 8 from that of the 200 μm scan area. The limiting background may be two magnitudes brighter or 18 $m_v/\widehat{\text{sec}}^2$.

The spreading of the image described by the tube MTF has been calculated to produce a 15% loss in the signal p.e. on a given sensor. Since the image is spread over two sensor scan areas, the time taken is 11.86 x 2 ÷ 0.85 = 28 seconds.

4.4.3 Sensor III

$$S/N = \frac{1}{\delta} = 7.1 = \frac{n}{\sqrt{n + 128}}$$

$$n = 109 \text{ p.e.}$$

The image is spread over two elements, but counting efficiency is not a factor,

$$\therefore \text{ signal rate} = \frac{17.3}{2} \times 0.85 = 7.35 \text{ p.e./sec}$$

$$t = \frac{109}{7.35 \text{ p.e./sec}} = 14.4 \text{ seconds}$$

Limiting background considerations are identical to Sensor II, and the limiting background is $18 m_v/\widehat{sec}^2$.

4.4.4 Sensor IV

Same as Sensor III except limiting factor is dark current and

$$t = \frac{(S/N)^2 (R_s + R_D)}{R_s^2}$$

The signal rate R_s = 7.35 (see paragraph 4.4.3). The dark current for the 50 μm sensor scan area is 500 p.e./sec and the time required is 469 seconds or 7.8 minutes.

Since the sensor will saturate on its own dark noise in 2.67 minutes, a memory and data processing equipment is necessary and $\frac{7.8}{2.67}$ = 3 sensor readouts are required.

4.5 GUIDANCE CONCEPTS

4.5.1 Concept I

In this concept (Figure 3-3) the target is moved a distance d onto the slit jaw, and the target centering mode is activated. The S/N, background, time to center, etc. are the same as for the track mode. The total operational time is the time to center, plus the time required to move the image onto the slit jaw.

4.5.2 Concept II

The areas on the slit jaws are examined for a period of time as shown in Figure 3-4. When the difference in the signals exceeds

a given threshold, an out of specification condition is indicated, and guidance concept I is implemented. It is assumed, for this concept and those to follow, that the image motion will be slow and that it will take at least 10-15 minutes for the image to wander a distance of one-tenth its width. Therefore, any guidance system which responds in less than this time will perform satisfactorily.

Calculations have shown that a motion of 10% of the image diameter will cause a change in photon arrival rate on the slit jaws of 5% of a full image. Because of this, the 23rd $m_v/\widehat{sec}^2$ background becomes significant (0.42 x signal) and the time required to achieve a given S/N ratio increases.

a) Sensor I

The desired S/N is 6.3 and it may be shown

$$S/N = S \Big/ \sqrt{S + 0.42S}$$

where S, the signal p.e. rate = $\frac{8.6}{20}$ = 0.43 pe/sec.

Under these conditions, the value of S = 56 p.e., and 2.2 minutes are required for each slit jaw, requiring 4.4 minutes to determine the out of specification condition. The total time is 4.4 minutes plus the 1.5 minutes for concept I or 5.9 minutes total.

b) Sensor II

Conditions are the same as for Sensor I, but both sides of the slit jaw are scanned at once. Thus 2.2 + 1.5 = 3.7 minutes are needed.

c) Sensor III

Sensor III is limited by the noise of the readout amplifier

$$S/N = \frac{S}{\sqrt{1.42S + 128}}$$

S = 105 p.e. and the rate of accumulating signal is 5% of 17.3 or 0.86 p.e./sec. This sensor will require 2 minutes to detect the out of specification condition, plus 1.5 minutes for Concept I, for a total of 3.5 minutes.

d) Sensor IV

This sensor is dark current limited, and the background is <<dark current.

$$t = (S/N)^2 \left(\frac{R_S + R_D}{R_S^2}\right)$$

R_S = 0.86 p.e./sec

R_D = 2000 p.e./sec, assume a 0.1 mm square scan area

t = 101,000 sec or 28 hr.

4.5.3 Concept III

The image is assumed to be entirely within the slit jaws, and the image motion δ, is taken as

$$\delta = W_I \times \frac{C_G}{C_C}$$

where W_I is the image diameter, C_G is the p.e. count during the guidance mode, and C_C is the p.e. count that was obtained during the track mode. Both C_C and C_G will contain uncertainties, which will root sum square with the beam position error which has been set at 0.07 W_I. Because of these factors, the accuracies required during track and guidance are 5%, and the S/N ≥20. This is the most severe requirement of any concept. Since this concept has the least promise, only the results will be given in Table 4-1. No results were shown for Sensor IV, since the time would have been in excess of 28 hours.

4.5.4 Concept IV

Here it is assumed that the image is larger than the slit, because of longer wavelengths present in the signal (500 nm) than those examined by the spectrograph, (300 nm) or because of deliberate defocussing of the image. The configuration is shown in Figure 3-5. For this concept, a scan area 50 x 120 μmeter will suffice, and 14% of the total target energy falls on the slit jaws. If d is the p.e. density, W_I the image width and k the fraction of W_I that the target moves, it may be shown as a first approximation that the error signal = $2k\ W_I d$, independent of the amount of energy spillover on the slit jaws. It may also be shown that if the error in determining the p.e. count (ε_n) on each slit jaw adds, that the error in determining the center (ε_c) is $\varepsilon_c = \frac{\varepsilon_n}{n} W_I$ where n is the p.e. count on one slit jaw.

a) Sensor I

$\varepsilon_n = \sqrt{n}$ and the error ε must be $\leq 0.1\ W_I$

$$0.1\ W_I \geq \frac{\sqrt{n}}{n} W_I$$

For a 50% counting efficiency and a photon rate of (0.14)(17.3), the time required to detect a motion of 0.1 W_I is 2.8 minutes.

b) Sensor II

Since both slit jaws are scanned simultaneously, and the operation is otherwise identical to Sensor I, t = 1.4 minutes.

c) Sensor III

It may be shown that

$$\varepsilon_c = W_I \frac{\varepsilon_n}{n} = \frac{\sqrt{n + 128}}{n} W_I$$

letting $\varepsilon_c = 0.1\ W_I$

$$n = 176 \text{ p.e.}$$

The p.e. rate is 0.14 x 17.3 = 2.4 p.e./sec

$$\therefore t = \frac{176}{2.4} = 73 \text{ seconds}$$

d) Sensor IV

It can be shown that

$$t = \frac{(S/N)^2 (R_s + R_D)}{R_s^2} \qquad R_s = 2.4 \text{ pe/sec} \quad R_D = 10^3 \text{ pe/sec}$$

$t = 17{,}361$ seconds $= 4.8$ hours

The results of the foregoing acquisition, track and guidance analyses are presented and summarized in Table 4-1. Note that the limiting background is $23 m_v/\widehat{sec}^2$ for all guidance concepts except Concept I. This is because Concept I is the only one which uses the entire image. The other concepts could be used with stronger backgrounds, but the time required would have to be increased until the S/N reached the desired value.

4.6 SLIT CENTER DETERMINATION

4.6.1 Concept I

This slit centering concept and those which follow are based on the assumption that the entire slit is flooded with light equivalent to an 18th magnitude star.

In this concept, 50 μmeter scan areas would be read out. The readouts would follow a pattern similar to that shown in Figure 3-6.

It can be shown that if X_1Y_1, X_2Y_1, $\cdots\cdots X_nY_1$ are the coordinates of the center of the sensor scan areas shown in Figure 4-3, then the X coordinate of the slit jaw center is

$$X_c = \frac{X_1 + A_s\left(k_1 - k_2\right) + X_4}{2}$$

Once the X_c is determined

$$Y_C = \frac{Y_1 + A_s\left(k_1 - k_2\right) + Y_4}{2}$$

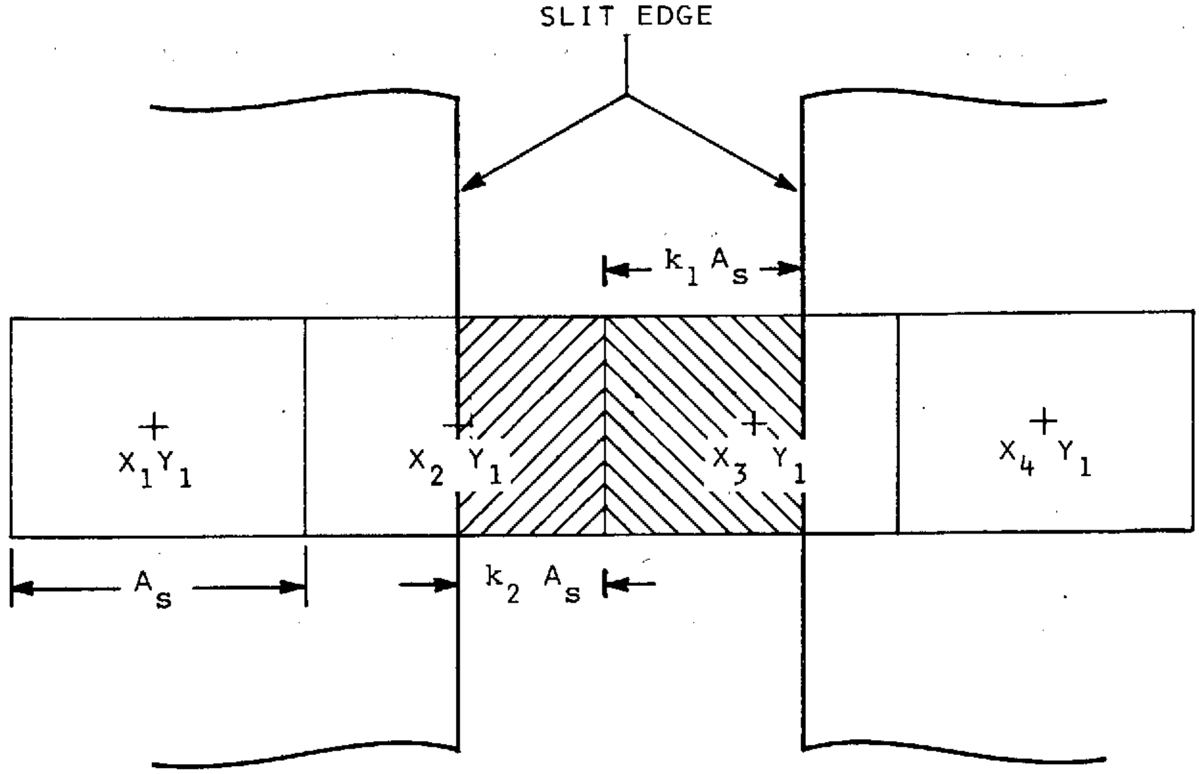

Figure 4-3. Slit Center Determination

Note that this method depends on slit jaws which have rectangular dimensions which are 100 μmeter or greater. For the light illumination specified, the p.e. count is 1730/second. For Sensors I and II, about 1.2 seconds of time would yield 1038 countable electrons, with an error of

$$\varepsilon = \frac{\sqrt{1038}}{1038} = 3.1\%$$

The time to scan a field of a given size would then be the same as in the search mode (see Table 4-1). For Sensor III, one second of time would yield a

$$\varepsilon = \frac{1}{S/N} = \frac{\sqrt{1038 + 128}}{1038} = 3.3\%$$

4.6.2 Concept II

Again assume that the slit is rectangular. Concept I may be used to determine the approximate slit center. The sensor scan area is then shifted in small increments (say 10 μmeters) until the sensor scan area readout is one-half the value that it was for a sensor scan readout which is 100% within the slit jaw, as shown in Figure 3-7. When this happens, the sensor scan area is half on the slit jaw, and half off. The position of the sensor scan area coincides with the edge of the slit jaw. When all four edges are found, the center may be determined. If it takes 10 attempts to determine each edge, and one second per attempt, 40 seconds are required to determine the slit center, not counting the time required for calculations.

4.6.3 Concept III

This concept will also work for circular apertures (pinholes) as well as rectangular slits. The approximate center is determined using Concept I. Again the sensor scan area is shifted, and a profile of the p.e. count vs. shift is made as shown in Figure 3-8. For a rectangular slit, the 50% points can be determined and used to find the edges of the slit. For circular pinholes, there is no "edge", but the center of the pinhole is the center of symmetry of the profile. In the case of the pinhole, the operation may have to be repeated twice to get an accurate determination. The first time, the value of X_c may be a little in error, but will be useful in obtaining an accurate value for Y_c. The new accurate Y_c is then used in scanning to determine X_c. If one second per profile point is used, and two X_c profiles and one Y_c profile is made with 20 points per profile, then 60 seconds is required to determine the center, not counting calculation time.

4.6.4 Concept IV

Fiducial lines in x and y are scribed and accurately located with respect to the pinhole or slit as shown in Figure 3-9. The position of the fiducial lines are found using Concepts I, II or III, and the position of the pinhole obtained from the relationship of the pinhole center and the fiducial X and Y values.

4.7 DYNAMIC RANGE

A desired dynamic range of 15 magnitudes (10^6) has been selected for the TAPS System. The photon arrival rate for a 23rd magnitude star produces a count rate of 17.3 p.e./sec at the photocathode, therefore the maximum rate of the photocathode would be 17.3×10^6 p.e./sec.

Sensor I is capable of producing pulses at this rate, and circuits are available which can count at a 20×10^6 Hz rate; therefore Sensor I can achieve the 15 magnitude range.

Sensor II reads all the sensor scan areas as the photons arrive. For a 6 mm square tube, and a 50 μmeter square scan area, 1440 scan areas must be read out. For a 23rd magnitude star and a 50% counting efficiency, the count rate is about 2.5×10^4. Assuming that 50 M Hertz counting is possible, the range for Sensor II is $50 \times 10^6 \div 2.5 \times 10^4 = 2000:1$. If it is desired to extend the range beyond this, neutral density filters or other means of optical attenuation must be provided.

The range of Sensors III and IV is limited by the capacity of their targets to integrate the charge linearly. The storage capacity* is approximately 2×10^{-14} farad/mm^2, and a target voltage of 4 volts yields a linear range of 5×10^5 p.e./mm^2. For a 50 μm square sensor scan area, 1250 p.e. may be linearly integrated and

*Lowrance, Sept. 1971 Report to the LST Steering Group.

stored. Since the target is spread over two sensor areas when the 50 μmeter scan area is employed, saturation on a 23rd magnitude star takes place after 145 seconds. For a star 15 magnitudes brighter, saturation will take place after 145 microseconds.

To achieve a 15 magnitude range, any or all of the following measures may be employed:

1) gating the high voltage of the gain stages on and off

2) reducing the high voltage of the gain stages to achieve an automatic gain control (AGC)

3) use an optical attenuator

4) use the target in a non-linear portion of its operating range and calibrate it.

It is estimated that the high voltage for a magnetically focussed vidicon can be switched on and off for a period of 1.5 milliseconds. This will yield a 10^5 (12.5 magnitude) range capability. Electrostatically focussed vidicons have been manufactured* with a special electrode which requires a much lower gating voltage than the electron multiplier section, and can be switched on and off in 150 μsec. The electrostatic tube does not possess the resolution (MTF) capability of the magnetic tube (600 lines/16mm at 5% MTF) and an f number of 320 would be required.

The reduction of the high voltage of the electron multiplier section may be performed continuously for the electrostatic vidicon, but the magnetic type requires that the voltage take on discreet values corresponding to $\sqrt[n]{V}$, where n = 1, 2, 3... and V is the high voltage nominal value. If this is not done, the

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*Conversation with Ralph Byer, Westinghouse, Elmira, N.Y.

electron beam focus point will shift. For the magnetic vidicon, this does not seem like a good way to achieve the desired result. If the full 15 magnitude range is desired, it would be better to gate the high voltage to achieve 12.5 magnitudes, and use the non-linear region of the curve or an optical attenuator to achieve the rest.

4.8 BRIGHT NEIGHBOR CONSIDERATIONS

Whenever the TAPS System is attempting to perform its search, track, slit center determination or guidance function, it must overcome the effects of "unwanted signal", which in reality is "noise." Noise sources such as tube dark currents and uniform background are readily defined and studied. One of the major sources of noise, and one which varies with every target, is the presence of a neighboring source of light, which injects unwanted signal into the area of the target.

Because every situation is unique, a general study cannot be made unless the situation is simplified. For this reason, the search and track modes were analyzed to determine the effect on their performance of a single, brighter neighboring line source. It has been assumed that the background is uniform at 23rd magnitude/$\widehat{sec}^2$ for this study.

4.8.1 General Considerations

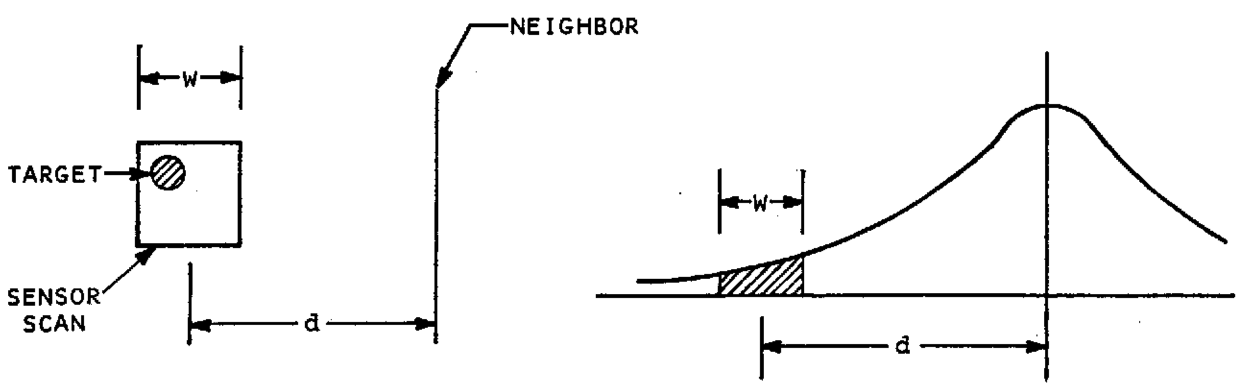

Figure 4-4. Energy Contribution of Bright Neighbor

A line source located a distance d from the sensor scan area which contains the target is assumed to have a gaussian line spread function as shown above. The energy density is assumed to be gaussian normal to the line, and constant parallel to the line. The sensor scan area integrates the energy density within its bounds, shown by the shaded area. As long as the total energy that the sensor scan area receives from the neighbor is less than some fraction of the energy that the sensor scan area receives from the target, the operation of the system is not affected. As this limit is exceeded, the S/N ratio decreases compromising the data quality. At some point, the S/N ratio will decrease below unity, and the target will be obscured. Since the search and track modes have different size scan areas and different criterias of succesful operation, separate studies are made for each mode. The general procedure followed for both modes was this:

A telescope image, under normal conditions, is assumed to contain 80% of its energy within one Airy disc, and to have a gaussian distribution. The gaussian function is integrated between the limits $(d + \frac{W}{2})$ and $(d - \frac{W}{2})$ for various values of d. The relationship between the area within the $(d + \frac{W}{2})$ and $(d - \frac{W}{2})$ limits, and the area under the entire gaussian curve is determined. The area between the limits corresponds to a certain amount of energy, and is set equal, depending on the mode of operation, to some fraction of the target energy on the sensor scan area. Since the area between the $(d + \frac{W}{2})$ and $(d - \frac{W}{2})$ limits is known with respect to the total gaussian area (total neighbor energy) the relationship between total neighbor energy and distance d may be established.

It should be noted that the distance d is the distance from the center of the sensor scan area to the center of the neighbor, not the distance from the target to the neighbor.

4.8.2 Search Mode

To establish a criteria for search mode, consider the fact that a picture of the scene will be available, so that the profile of the bright neighbor on the scene may be drawn and its effect calculated. Under these conditions, the uncertainty in the total p.e. count of the neighbor is important, not the p.e. count itself. Assume that the noise introduced by the neighboring source on a sensor scan element should be about one-ninth of the signal due to the target. The noise (uncertainty) on a scan element is equal to the square root of the photoelectron count due to the neighbor. Therefore, the photoelectron count on a sensor scan element caused by a neighboring line source is permitted to be one-third the photoelectron count of the target. The energy from the target may or may not be wholly contained on the sensor scan area, which is 200 μm square, depending on where its center is located. For this analysis, it is assumed that 75% of the energy from the target falls within the sensor scan area.

The procedure outlines in para. 4.8.1 was followed, both for the 300 nm diffraction limited case and for a degraded image case, where 70% of the energy was assumed to fall within 2 Airy discs (234 μm). The results are shown in Figures 4-5 and 4-6.

4.8.3 Track (Centering) Mode

The centering is expected to be as automatic as possible. Therefore, the total photon count from the neighbor is important, not its variation. The target is to be centered to within 10% of its diffraction limited diameter, which requires 14% accuracy in the photon readout. Three (3%) percent has been chosen as the ratio between the neighbor to target photons. About 50% of the total target photons will be on a 50 μm scan area. Therefore, the neighbor p.e. count on the sensor scan area is permitted to be 1.5% of the total target p.e. count.

The results for the track mode, assuming a 300 nm diffraction limited target and a 50 μm scan area, is shown in Figure 4-5. A degraded image case, 70% of the energy in 2 Airy discs, was considered with the sensor performance also degraded.

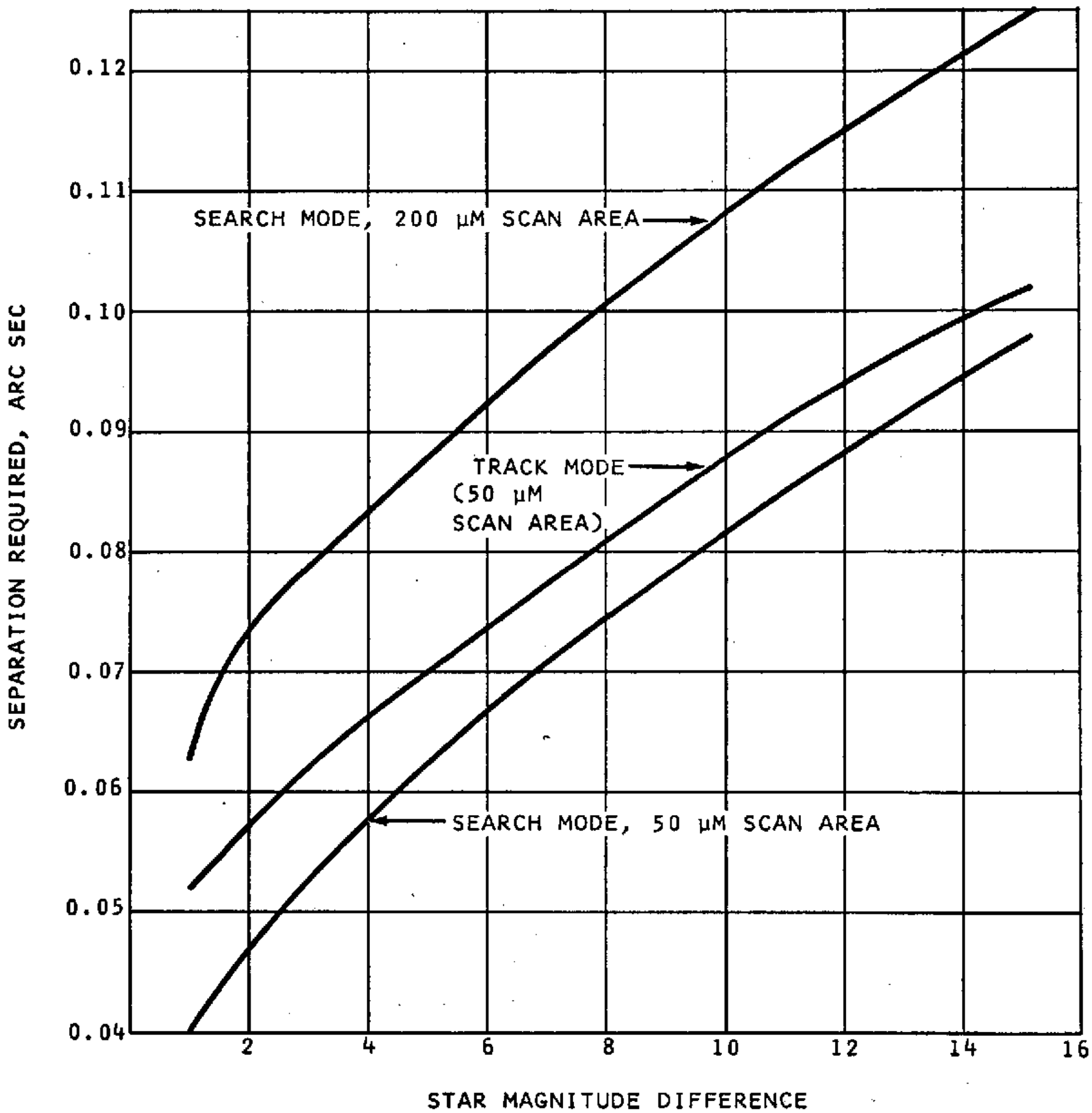

Figure 4-5. Required Separation, Normal Image

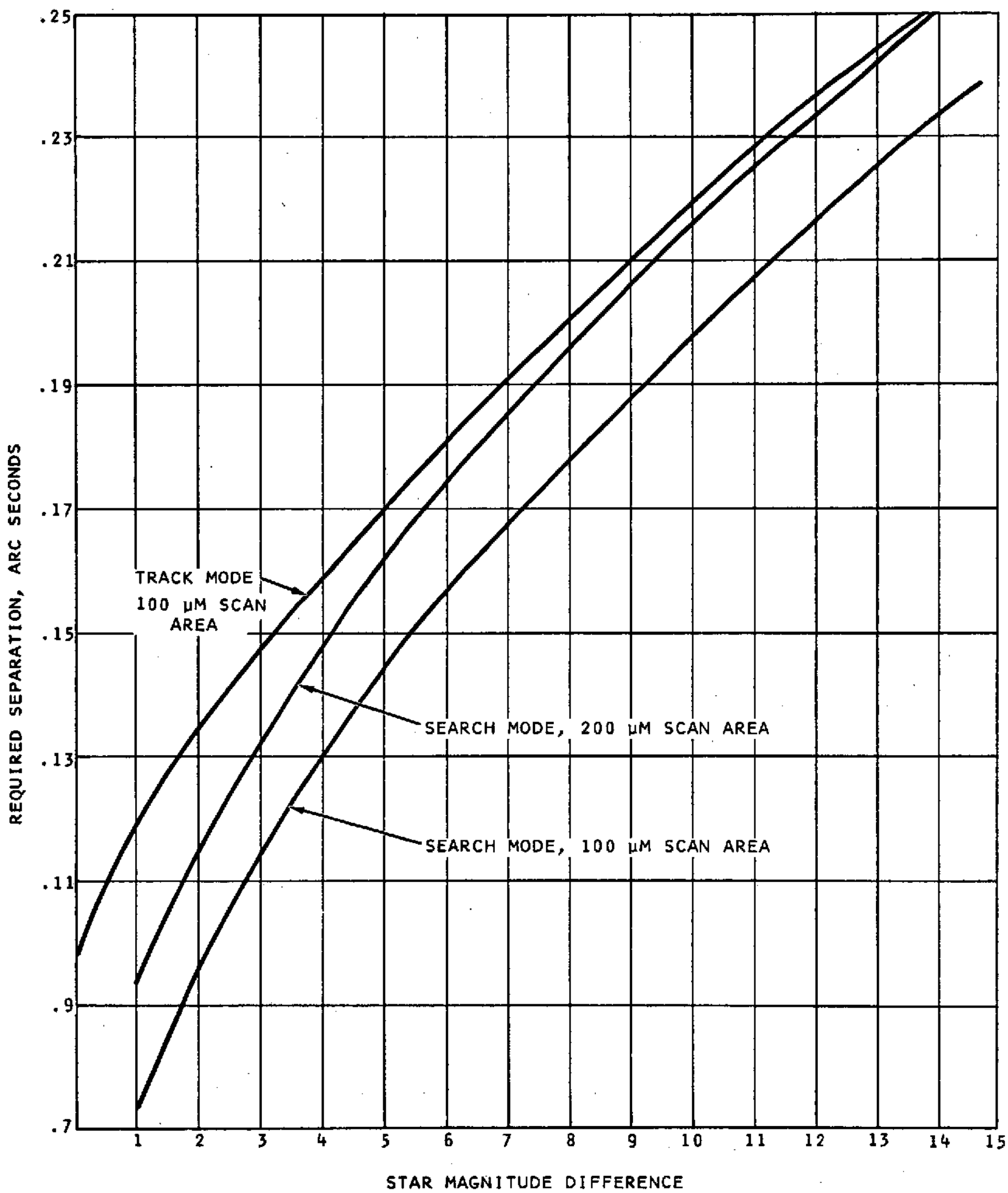

Figure 4-6. Required Separation, Degraded Image

and that the sensor scan area was 100 μm square. The results of this study is shown in Figure 4-6.

4.9 SENSITIVITY AS FIELD CAMERA

One of the functions of the TAPS system is to transmit a picture of the scene to the astronomer. Therefore it is possible to use the TAPS as a camera either in place of or in conjunction with the high resolution camera, within certain limits. The high resolution camera, which presently operates at f/96, has a field view of 170 microradians using a 50 mm sensor. The TAPS field of view is 25 microradians and it uses a 12 mm sensor. If a 50 mm sensor were used in TAPS the field of view would be 105 μradians, and the volume required for the system would increase considerably.

Because it has a larger f number than the present field camera, the TAPS system is capable of higher resolution that the f/96 camera. For a near diffraction limited 3000Å image, the improvement is on the order of a few thousandths of an arc second.

The limiting magnitude for the TAPS system can be calculated as follows using Sensor III:

Photocathode Dark Current = 4 p.e. mm^{-2} sec^{-1}

For a 50 μm square sensor scan area

Dark Current, I_D = 4 p.e. mm^{-2} sec^{-1} x 25 x 10^{-4} mm^2
= 10^{-2} p.e./sec

Sky Background I_B = 3.0 p.e./mm^2 x 25 x 10^{-4} mm^2 (1)
= 0.0075 p.e./sec for 23rd mag/$\widehat{sec}^2$

$I_D + I_B$ = 0.018 p.e./sec

For a 1 hour exposure

$I_D + I_B$ = 0.018 x 3600 = 64.8 p.e.

(1) Based on 17.3 p.e./sec for 23 m_v and scale factor of 2.4 mm/$\widehat{sec}$

Assuming a S/N of 2 defines the limiting magnitude

$$2 = \frac{S}{\sqrt{S + N_R + I_D + I_B}}$$

where N_R is the readout noise of the SEC = 128 pe

$$2 = \frac{S}{\sqrt{S + 128 + 65}}$$

solving, S = 30 p.e.

The signal rate for a 23rd magnitude target has been determined as 17.3 p.e./sec. Since this is spread over four 50 μmeter scan areas S = 4.3 p.e./sec for a 23rd magnitude target. Solving for the magnitude difference (Δm_v) from a 23 stellar magnitude:

$$\frac{4.3 \text{ p.e./sec}}{2.512^{\Delta m_v}} \times 3600 \text{ sec} = 30 \text{ p.e.}$$

$$\Delta m_v = 6.78$$

Therefore, the limiting magnitude for the TAPS system used as a field camera against a uniform 23 $m_v/\widehat{sec}^2$ background for a 1 hour exposure is 29.8 m_v.

The above estimates of sensitivity were made assuming no transmission losses. A sample TAPS configuration shown in Figure 5-1 can be considered a worst case situation as far as the number of reflections are concerned. The reflecting surfaces are used for compactness and/or configuration control. For the TAPS at visible wavelengths, the approximate losses will be:

2 lens at 95% transmission each - 90%
4 mirrors at 90% efficiency each - 66%

This will result in a TAPS system loss of 41% which is equivalent to 0.67 of a stellar magnitude.

This loss combined with the telescope will probably result in 29 m_v as the limiting magnitude under the assumed conditions.

Section 5

CONFIGURATION

There are many variations available for configuring the TAPS system to the L.S.T.

The one shown in Figure 5-1 is modeled to adapt to G.S.F.C.'s concept #4 of the S.I. package.

5.1 INTERFACE POSSIBILITIES

The TAPS Sensor Unit can be mounted to the same station and have the same access possibilities as the offset star trackers. Each instrument module that will utilize the TAPS would contain a set of specular slit jaws. This allows each instrument to have mechanical cognizance from its entrance slit through the output for fabrication and functional testing. The sensor assembly should weigh about 11.6 Kg and the power dissipation should not exceed 6-8 watts. The sensor unit is 12 x 16 by 40 cm in length.

5.2 TAPS SENSOR CONFIGURATION

The TAPS System consists of two main sections; a sensor package on the stationary heat sink plate which includes the electronics and a magnifying relay focussed onto the slit location and a back illuminated slit assembly on each of the spectrograph instrument modules. The system is shown conceptually on Figure 5-1.

The working of the system is very simple. The sensor is a camera focussed on the slit area, five arc seconds of telescope field of view. Within this field is the slit as seen by its back illumination and the star by specular reflection from the area surrounding the slit. This reflecting surface is tilted six and one half degrees, little enough to have no effect perceptible on the focus at the ends of the slits and large enough to get the sensor relay clear of the telescope field of view domain of one and one-half milli-radians.

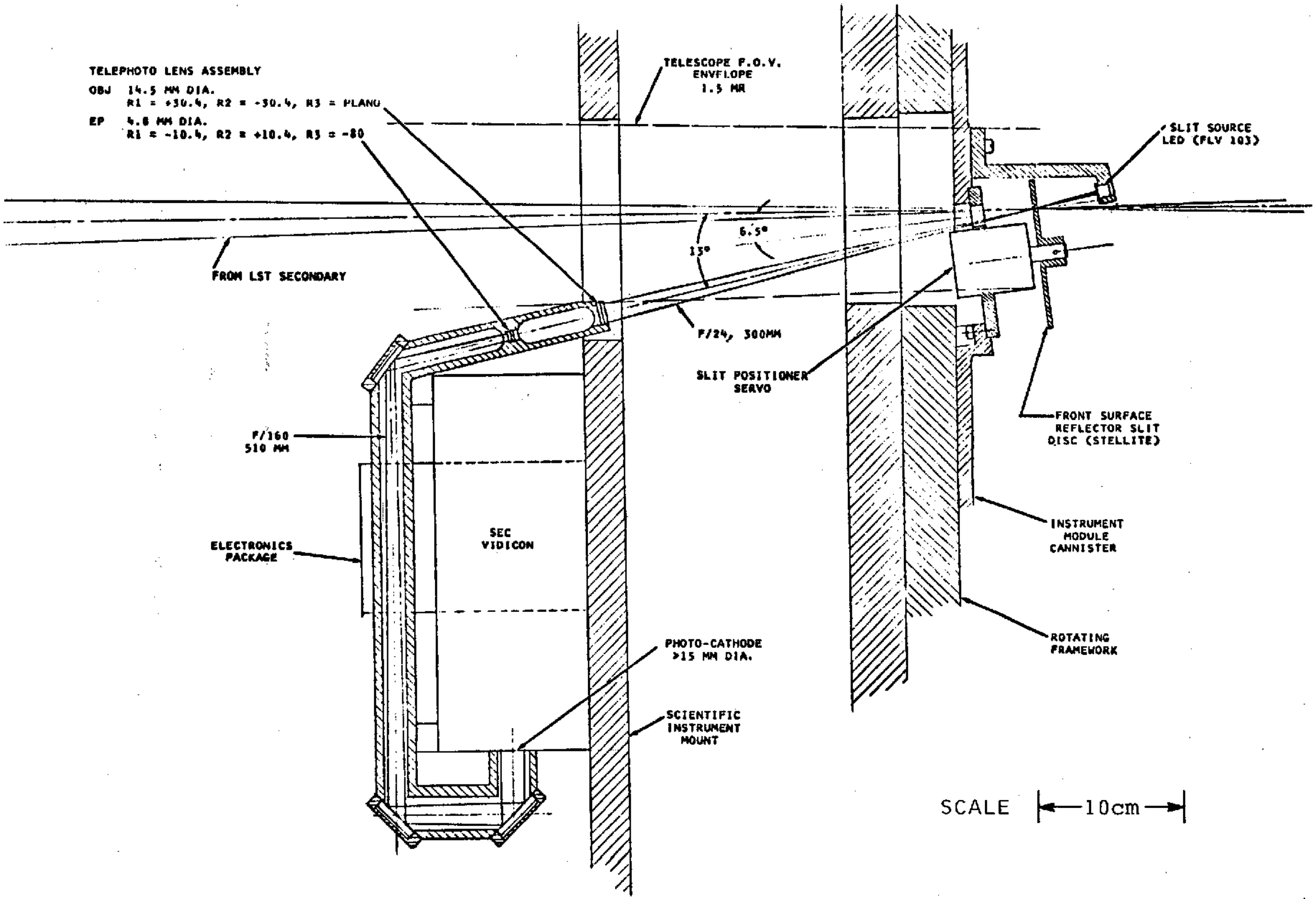

Figure 5-1. Target Acquisition and Position System Installed in GSFC Concept of Scientific Instrument Mount

The back illumination of the slit is by an LED. The source area is large enough to fill the aperture of the camera relay while being far enough back from the slit to clear the main starlight f/24 bundle directed toward the instrument module optics.

The slit is cut in a mirrored disc mounted on a precision rotary positioner for those instruments which require a choice of slit dimensions.

The sensor package relay is a telephoto type objective working at finite conjugates to produce a 6.6 times magnified image of the slit area on the sensor. The approximate optical prescription is shown on the drawing.

The sensor is a SEC Vidicon with a linear field of view of fifteen millimeters defined by its photocathode.

The sensor unit, the optics unit of the relay lens and folding mirrors and the electronics package are received to a common base for ready removal of the camera as a package for in orbit mainten-ance or replacement.

Section 6

RECOMMENDATIONS

6.1 MODES

The recommended mode for search is semi-automatic pattern recognition. The S/C control system and the knowledge of the target position will insure the target falling within the 25 μradian field of view of the TAPS. The target identification may be automatic, semi-automatic or manual, depending on its nature. A single isolated star in a 25 μradian field can be identified automatically, but a low contrast part of an extended source will require operator/ astronomer decisions. Verification is a pattern recognition task, and is best accomplished by the operator and suitable visual aids, considering the vast number and types of targets.

Track is best accomplished using an automatic mode wherever possible, since this is the fastest and most accurate. Semi-automatic modes should only be reverted to when the targets are too complex or moving too rapidly for automatic centering. In some cases of moving targets, where the S/C is not in ground contact, automatic operation is necessary. In this case, the TAPS System is not used, and the S/C control system centers the target at lesser accuracies.

Guidance, using TAPS, is also best performed automatically because it is the fastest and most accurate. Only where the target is complex should other modes be used.

6.2 CONCEPTS

Guidance Concept III (para. 3.4 and 4.5.3) is unacceptable because of the time required and the fact that the entire target energy must be contained within the slit. Guidance Concepts I, II and IV, all have merit, and at this time no definite choice can be

made. Concepts I and II are very similar and use the least amount of time because they use the entire image, but they involve moving the image onto the slit. S/C operations and other project personnel should be consulted as to the impact of this maneuver. Concept III uses a partial image. The partial image is obtained because the image is normally larger than the slit, or will be made so by defocussing. If it becomes necessary to enlarge the image by defocus, the impact of such a maneuver on S/C performance will have to be evaluated. It should also be kept in mind that this approach depends on a symmetrical image, which in turn is dependent upon near diffraction limited performance. At this time, Concept IV appears to be the best because it does not interfere with the operation of the rest of the S/C, provided that the near diffraction limited performance is achieved.

Determination of the slit center is best accomplished using Concepts III and IV. Concepts I and II depend upon a rectangular edge and an image which is smaller than the slit. Concept IV is the most accurate because it can be calibrated on the ground and because the fiducial marks may be constructed such as to make their position determination optimum. For this reason, Concept IV is the recommended one.

6.3 SENSORS

Sensor III (para. 4.2.3) at this time is a clear best choice for the TAPS System. Sensor IV is not acceptable because its dark current at the specified temperature is so large that as much as 28 hours, plus a data processing system is required to achieve the desired S/N ratio for guidance. Sensor II has the best potential, but it requires data handling, which is not feasible, and a memory. In addition, channel multipliers at this time do not possess the desired resolution. Sensor I possesses many fine qualities such

as simplicity, ruggedness, insensitivity to amplifier readout noise, and photon counting ability, but it does require a data processing system because it has no memory. It's largest disadvantage is that it only accumulates and reads out data from one sensor scan area at a time due to its aperture. The result is that in excess of one hour is required to provide a 25 μrad picture for the designated 23rd magnitude target. Sensor III can integrate and store the scene for a period of hours, which means it doesn't require a memory. It possesses the required resolution and a dark current which is low enough, and sufficient electron multiplication to minimize readout noise, such that the time required to perform any operation (search, track, slit center determination and guidance) are acceptable.

Therefore, Sensor III, of which the SEC Vidicion is a prime example, is recommended for the TAPS application.